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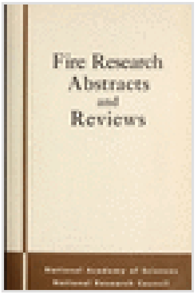

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FIRE RESEARCH ABSTRACTS AND REVIEWS

Robert M. Fristrom, Editor

FIRE RESEARCH ABSTRACTS AND REVIEWS will abstract papers published in scientific journals, progress reports of sponsored research, patents, and research reports from technical laboratories. At intervals, reviews on subjects of particular importance will be published. The coverage will be limited to articles of significance in fire research, centered on the quantitative understanding of fire and its spread.

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FOREWORD

Two review articles introduce this new volume of *Fire Research Abstracts and Reviews*. "The Physics of Fire Whirls" is by Professor B. R. Morton who wrote the lucid review of "Wind and Fire" in *Fire Research Abstracts and Reviews* **8**, 75–82 (1966). The second article, "Dust Explosions," is by a newcomer to the journal, Mr. J. W. Hughes. His summary of this complex field is interesting and informative.

Two new digests concerned with fire research have been instituted—"U.S. Navy Fire Research Bulletin" by the Naval Research Laboratory and "Research Report Digests" by the Federal Fire Council. Both are commendable and bear the signature of Dr. R. L. Tuve. They deserve a wide distribution.

It has been called to the Editor's attention by Dr. U. Bonne, one of FRAR's abstracters, that the "abstracts" in the journal are often more in the nature of short reviews than abstracts in the true sense, since the writers often include valuable comments and give technical evaluations and judgments of the article. The Editor is grateful to Dr. Bonne and hereafter Abstracters will be known as Reviewers. A reprinted abstract that has been written by the author of an article will continue to be designated as an "Author's Abstract."

A complete article from the U.S.S.R., "Flame Propagation When Two Successive Reactions Take Place in a Gas," translated by Mr. L. Holtschlag of the Applied Physics Laboratory, The Johns Hopkins University, is included in this issue.

A broad spectrum of Japanese work of an earlier date is offered in the form of English abstracts. This material has been in the hands of the Editor for some time awaiting translation. From these abstracts it is obvious that important fire research is being done in Japan and that some way should be found to provide access to this material for those limited to the English language. Solutions to this problem are presently being investigated.

Robert Fristrom, *Editor*

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THE PHYSICS OF FIRE WHIRLS*

B. R. MORTON

Monash University, Australia

Several papers on concentrated fire vortices were presented at the 1967 Mass Fire Research Symposium in Washington, and the resulting discussion of dynamical effects on large fires due to organized vorticity ranged from the importance of rotation in fire storms through the structure of fire tornadoes to the role of fire devils in extensive fires. During the discussion it was suggested that a straightforward account of features of concentrated vortex behaviour might be helpful to fire researchers, and this paper is an attempt at such a review; it includes discussion of the origin, generation, and amplification of vorticity in fluids, of the macrostructure of concentrated vortex cores, and of the appropriate conservation relationships.

Introduction

Dust devils, waterspouts, and tornadoes are dramatic features of atmospheric motion, and their counterparts, fire devils, fire whirls, fire tornadoes, and perhaps fire storms have attracted considerable interest in fire studies during recent years. The character and scales of motion of these concentrated fire vortices may be illustrated by brief descriptions of three actual fires.

The Project Flambeau experimental fire of June 14, 1966 has been described by Gaines (1967) and Broido (1967), among others. The fuel bed consisted of a regular rectangular array of two hundred and forty piles, each containing some twenty tons of dry fuel, the whole extending over an area of about 320×345 m². The day of the fire was clear and dry with wind initially "calm to very light" (Gaines) to a height of 5,500 m, and with lapse rate approximately dry adiabatic. Individual ignition of the piles which started at 09:00 hr was completed within 32 sec, and the fire built up rapidly to reach a maximum intensity within six minutes; soon after that the smoke began to lighten and become translucent, and later transparent. Gaines does not specify the ambient wind further, though he refers to the east as the lee side of the fire; however Nielsen (1967), in presenting initial results for the growth of the fire-induced wind within the fire zone during the first 40 min, states that the "prevailing wind was from the west at approximately 1.5 m/sec; and Broido (1967) in a perceptive commentary dictated on the spot† described conditions as essentially windless at ignition, with the smoke column blowing "slightly to the east" of north in the earliest stages, but with the wind

* This paper was presented at the Mass Fire Symposium held at the Forest Research Institute, Canberra, Australia from 10–13 February, 1969, and arranged by the Defence Standards Laboratories under the Technical Co-operation Programme. It appears in the Proceedings of the Symposium and is reproduced by permission of the Symposium Sponsors.

† It is difficult to overemphasise the value of having one or more skilled but uncommitted observers recording running commentaries on tape from the outskirts of the fire.

"definitely coming from the west" after 40 min, and after 90 min, in the dying stages of the fire, a "pretty strong natural wind blowing from the west." Thus the light air at ignition apparently developed definitely as a westerly during the course of the fire, bending the smoke plume over and carrying it off to the east.

Gaines reports that the first fire whirl was observed 14 min after ignition, and that one observer counted about 50 whirls in the following 30 min and 150 in $4\frac{1}{2}$ hours. Whirls sometimes formed singly, often in pairs, and occasionally three or four at a time; they varied considerably in size and velocity, but were typically 6 to 15 m in diameter and 300 to 900 m tall; they were sinuous in shape, grew quickly, seldom lasted more than 2 to 3 min, and were often luminescent; and most remained within the fire area, though a few migrated out of it in the later stages.

During the first two hours of the fire Broido (1967) walked the bounds within 150 m or so of its edges, recording his impressions directly. From this range the "first very distinct whirl" appeared 28 min after ignition, and thereafter whirls or "twisters" figure prominently in his commentary. There appear to have been two centres of fire-whirl activity to the "north and south of the centre on the east edge" of the main burning area; that is, broadly towards the crosswind corners of the downwind edge of the active fire area. In the later stages of the fire Broido saw as well numbers of "small whirls . . . pick up momentarily" in the outer parts of the region, and especially over smouldering piles. He commented that fire whirls were playing little part in the dynamics of the Flambeau fire, but that they were centres for most of the stronger winds and were responsible for much of the transport of sizable firebrands.

Fire whirls of similar type are a well-known feature of the plumes at oil-well fires; and Dessens (1962) has reported that smoky fire devils some 10 m in diameter and 200 m high are frequently generated in the bent-over convection plume produced by the Meteotron (over an array of oil burners capable of a maximum heat output equivalent to 7×10^5 kW). The Meteotron fire devils appear under crosswind conditions when the fire plume is inclined, and the lower parts of these vortices may be advected many burner diameters downwind during the few minutes of their lifetime.

The second representative fire whirl had the more violent character of a fire tornado, and occurred during the Poleline Fire in Southern California during a day in 1958 when ambient temperatures exceeded 100°F. The fire was burning across chaparral flats towards the San Bernadino Mountains into a cross-mountain wind, and the tornado formed at the time of a line-burning operation which may well have fed vorticity into the main fire column. Fire vortices in this range exhibit layers of strongly turbulent spiralling inflow near the ground with wind speeds to 50 m/sec; but as the inflowing air is channelled up the vortex core aloft, the larger scales of its turbulence are quickly damped by the inner rotational motion. The resulting turbulent entrainment into the vortex core is appreciably less than that of normal buoyant plumes, with a corresponding decrease in the combustion rates of ascending fuel vapour; and through the smoke of the Poleline fire tornado a flickering core of flame was weakly visible to an estimated height of 600 m.

The 1943 fire storm at Hamburg provides the third illustration in ascending order of scale, though it has yet to be demonstrated conclusively that this was a gigantic fire whirl, and differences of opinion remain. Thus Baldwin and North (1967) effectively ignored the possibility of large-scale organised vortical motion in seeking practical limits of definition for fire storms and in constructing a simple model, while Emmons (1965) inclined to the view that velocities such as those observed in the Hamburg Fire could scarcely be generated by the buoyancy field alone and must probably require the presence of a gigantic vortex, and Ebert (1963) uncovered eyewitness evidence that "a very distinct counter-clockwise wind pattern" developed during the storm. Ebert has given one of the clearest reconstructions. The level of rainfall, which had been average in the few weeks before the fire storm had been more than offset by the prolonged high temperature of these weeks, causing extreme drying of all woodwork. The air raids were made under unstable conditions of atmospheric stratification, and the bombing was so intense that an almost totally committed central region of fire roughly 13 km^2 in area developed within an hour; and this central region continued to burn with increasing intensity for several hours. It has been estimated that street temperatures reached 750°C. The extreme intensity of the fire source coupled with the ambient instability to produce a huge convective column some 3 km across, capped by a cumulonimbus with anvil approaching heights of 10 km. Flyers described the fire plume as stormy at 4 km; and at ground level men were swept off their feet near the edge of the fire (suggesting a wind of force 12 on the Beaufort scale), cars rolled over (perhaps force 10), and trees of 1 m diameter uprooted (force 10, or more in dry firm ground). Thus winds of hurricane intensity were indicated at the edge of the fire storm, though it is still uncertain to what degree this was due to the development of a huge vortex.

In summary, fire vortices are observed over a very wide range of length and velocity scales from small fire devils, which are probably best regarded as a natural part of fire turbulence having negligible dynamical or other significance, through fire devils of normal size, which have little or no special dynamical significance but may play a significant role in distributing firebrands and may present some hazard to fire fighters, to fire tornadoes and (possibly) fire storms, which dominate the dynamics of their fires and may lead to situations of extreme hazard.

The Role of Ambient Vorticity.

The study of fire vortices involves the origin of their rotation and also the possible mechanisms by which it is amplified. The rotational nature of the flow may be specified by its vorticity (which is twice the local angular velocity), and we may conveniently discuss the vorticity field in terms of vortex tubes, which align with the local vorticity, have constant strength (cross section × vorticity = circulation, for narrow tubes), and move with the fluid. In the absence of shearing forces, regions of homogeneous incompressible fluid which are initially irrotational remain in a state of irrotational motion, while those which are rotational may suffer local amplification (or diminution) of vorticity, but cannot become irrotational. Real fluids suffer in addition viscous and Reynolds stress diffusion of vorticity down vorticity gradients, though this is often a relatively slow process and in many cases does not greatly affect our discussion. Diffusion does, however, provide a limit to the magnitude of the vorticity gradients that can be established or maintained in a flow.

The vorticity of concentrated vortices must be generated locally in the fluid, or be produced by local amplification from a more extensive background of weak vorticity arising from the earth's rotation or some other source. Thus in a tank of water we can create visible vortices at the edges of a plate moved through the liquid, or over a sink through which the liquid is slowly drained.

Strong background rotation will exert a considerable constraint on concentrated vortices, while weak background rotation can serve as the source for vortex production by local amplification without subsequently exercising any significant constraint on the vortices once formed. A general assessment of the dynamical effect of background rotation can be obtained from the Navier-Stokes equation for disturbance flow with velocity $\mathbf{v}$ in a fluid region otherwise having rigid body rotation with angular velocity $\mathbf{\Omega}$,

$$(\partial\mathbf{v}/\partial t)+\mathbf{v}\cdot\nabla\mathbf{v}+2\mathbf{\Omega}_\wedge\mathbf{v}=-(1/\rho)\nabla p+\nu\nabla^2\mathbf{v}+[(\rho-\rho_a)/\rho]\mathbf{g}, \quad (1)$$

where $\mathbf{v}$ is measured relative to axes rotating with constant angular velocity $\mathbf{\Omega}$ and $(\rho-\rho_a)\mathbf{g}$ is the buoyancy force in nonhomogeneous fluids with ambient density ρ_a which may vary with height. The relative roles of the inertial forces $\mathbf{v}\cdot\nabla\mathbf{v}\sim V^2/L$ and Coriolis forces $2\mathbf{\Omega}_\wedge\mathbf{v}\sim|2\mathbf{\Omega}|V\sim 2\Omega V$ for a given flow may be estimated in terms of the characteristic scales of velocity V and length L measured in planes $\perp\mathbf{\Omega}$ as

$$\left|\frac{\text{inertial forces}}{\text{Coriolis forces}}\right|\sim\frac{V^2/L}{2\Omega V}\sim\frac{V}{2\Omega L},$$

where $\text{Ro}=V/2\Omega L$ is the Rossby number for the flow. Just as the Reynolds number $\text{Re}=VL/\nu$ provides a measure for the relative importance of inertial to viscous forces over the flow as a whole, the Rossby number serves as a measure of the relative importance of inertial to Coriolis forces for a flow as a whole. We note that motion parallel to the rotation axis $\mathbf{\Omega}$ introduces no Coriolis force, and that scales V and L must necessarily be taken for motion in planes $\perp\mathbf{\Omega}$; in fact, fire vortices, like dust devils, waterspouts, tornadoes and hurricanes, are essentially erect or upright flows and we find ourselves concerned principally with the vertical component of the local background rotation.

An alternative interpretation for the Rossby number may be given in terms of the total vorticity $\boldsymbol{\omega}+2\mathbf{\Omega}$: the appropriate scale for relative velocity in the direction $\mathbf{\Omega}$ is V/L, and hence the Rossby number

$$\text{Ro}=\frac{V}{2\Omega L}=\frac{V/L}{2\Omega}\sim\left|\frac{\boldsymbol{\omega}}{2\mathbf{\Omega}}\right|\sim\left|\frac{\text{disturbance vorticity}}{\text{background vorticity}}\right|.$$

In middle lattitudes the *vertical* component of the background field due to the earth's rotation is about 1×10^{-4} rad/sec, and some roughly representative Rossby numbers for geophysical and fire vortices are:

	L	V	Ro
dust devils, fire devils	10 m	10 m/s	1×10^4
waterspouts	100 m	30 m/s	3×10^3
tornadoes	300 m	80 m/s	3×10^3
fire tornadoes	400 m	40 m/s	1×10^3
Hamburg fire storm	3 km	50 m/s	2×10^2
hurricanes	1000 km	100 m/s	1

and by contrast:

mesoscale ocean eddy	100 km	1 m/s	1×10^{-1}.

Thus we infer that even though concentrated atmospheric vortices may derive their vorticity from the rotation of the earth it is only at hurricane size that they suffer significant lateral constraint due to external rotation; however, the behaviour of mesoscale and larger ocean currents is dominated by the rotation of the earth. Fire vortices are not constrained by the earth's rotation; they may, of course, grow in a neighbourhood of enhanced background vorticity, but we see that the local ambient vorticity would need to be increased by some three orders of magnitude to exercise any appreciable constraint.

We are now in a position to interpret the observed behaviour of draining vortices (or "bathtub vortices"). Typical scales are perhaps 10^2 cm for L and 1–10 cm/sec for V, yielding $\mathrm{Ro} \doteq 10^2$–10^3 (based on $2\Omega \doteq 10^{-4}\ \mathrm{sec}^{-1}$). At these values of Rossby number it is clear that the vortices produced by normal draining are unlikely to depend on the background rotation of the earth but will depend rather on the vorticity generated in filling the tank or on the geometric configuration. We note also that

$$\left|\frac{\text{local acceleration}}{\text{Coriolis force}}\right| = \left|\frac{\partial \mathbf{v}/\partial t}{2\Omega \times \mathbf{v}}\right| \sim \frac{V/T}{2\Omega V} \sim \frac{1}{2\Omega T},$$

so that rapid draining (which also produces large Ro as in general $T \sim L/V$) fails to produce a vortex, whereas *very* slow draining of a tank free from extraneous disturbances is found always to produce a cyclonic vortex directly from the rotation of the earth (Andrade, 1963).

The Production and Amplification of Vorticity.

Fire vortices can form only where vorticity of appropriate strength with approximately vertical orientation is generated directly, is amplified from a weaker background, or is convected into place by the main flow.

The rate of change of relative vorticity $\boldsymbol{\omega}$ moving with an element in a fluid having uniform background vorticity 2Ω is represented by the Helmholtz equation,

$$(\partial \boldsymbol{\omega}/\partial t) + \underbrace{\mathbf{v}\cdot\nabla\boldsymbol{\omega}}_{\text{convection}} = \underbrace{(\boldsymbol{\omega}+2\Omega)\cdot\nabla\mathbf{v}}_{\text{local amplification}} + \underbrace{\nu\nabla^2\boldsymbol{\omega}}_{\text{diffusion}}$$

$$\underbrace{-\nabla(1/\rho)\times\nabla p - \nabla\left(\frac{T-T_a}{T_a}\right)\times\mathbf{g}}_{\text{local generation}}, \quad (2)$$

where p is the dynamic pressure and $T_a(z)$ the ambient temperature at height z.

The ambient level of vorticity in a particular neighbourhood may be enhanced by convective transport from another part of the flow; and this mechanism is responsible both for the advection of fire devils out of the fire zone and for the advection of naturally occurring vorticity into the fire. However, atmospheric vorticity in the earth's boundary layer has a predominantly horizontal orientation, and so has rather limited significance in the generation of fire vortices (which are typically oriented vertically and require a background of vertical vorticity in which to grow).

The vorticity of an individual fluid element may be increased in the following ways:

(1) Local amplification by stretching and bending of vortex tubes. The mean vorticity in an incompressible fluid is amplified locally in direct proportion to the

proportional stretching of the absolute mean vortex tubes. A section of vortex tube preserves its angular momentum about its axis under extension along that axis, and so increases its angular velocity (and vorticity) in direct proportion to its relative extension; a skater achieves high spin rates in a related way by lowering her arms close to her spin axis. This is the basis for local amplification of vorticity by convergence, and at least in small to mesoscale phenomena in the atmosphere appears generally to be associated with strong convection and an underlying boundary. The vorticity is correspondingly reduced in associated regions of vortex shortening.

The pressure p_{axis} on the axis of a vortex tube is less than that p_{edge} at its boundary surface by an amount,

$$\Delta p = p_{\text{edge}} - p_{\text{axis}}$$

$$= \int_0^R (\rho v^2/r)\,dr,$$

which is a strong function of the local radius R of the tube. Figure 1 shows a sketch of an isolated vortex tube with surface pressure p_{edge}, supposed constant, and it may be seen that the axial pressure is reduced in a stretched section of the tube. Thus a local constriction of a vortex tube (associated with a local enhancement of vorticity per unit section) has always an associated axial pressure gradient acting in such a direction as to induce axial inflow into the stretched or constricted section of vortex tube destroying its enhancement of vorticity. Concentrated vortices can survive only while some mechanism prevents their destruction by inflow from the "ends"; moreover, the pressure deficits in strong vortices are large, and may exceed 200 mb for violent tornadoes.

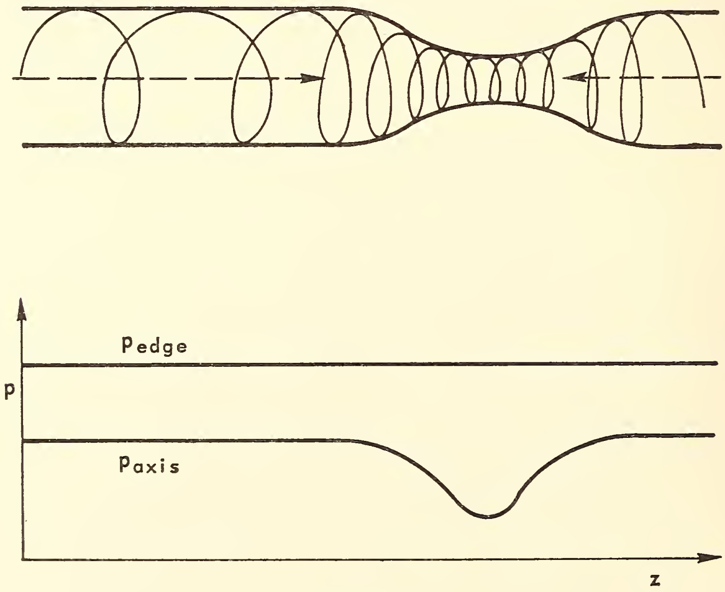

FIGURE 1

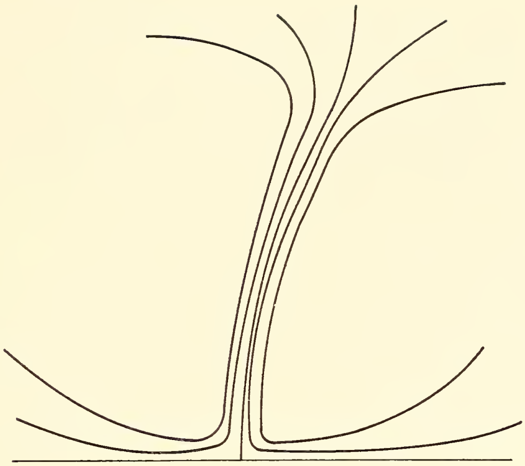

FIGURE 2

Vortex tubes cannot terminate either within fluid regions or on stationary rigid boundaries, and only occasional vortex lines can terminate at fixed boundaries (c.f., a dividing streamline at a stagnation point). Thus "concentrated vortices" must always consist of thin sections of vortex tube which "fan out" at either end (Fig. 2). We are now able to understand why concentrated vortices growing in a zone of convergence are almost always "terminated" at their lower ends at the ground (for waterspouts the sea), which serves to restrict inflow to the core, and are "terminated" aloft in regions of strong buoyant convection which prevents backflow into the core.

(2) Diffusion down vorticity gradients form fluid rich in vorticity. Concentrated vortices are likely to breed directly in the vorticity-rich regions rather than those towards which vorticity is diffusing. However, diffusion plays a vital role in limiting the degree to which vortices can be concentrated and strengthened by stretching.

(3) Direct generation of vorticity wherever level surfaces of density (temperature) are inclined to those of dynamic pressure or of gravity. Both of these generation mechanisms are important at meteorological "fronts," where a thin mixing zone separates two air masses of different temperatures, and frontal systems are likely to be rich in vorticity. However, the vorticity generated in this way is again approximately horizontal and is unlikely to play a vital role in the generation of fire vortices.

(4) Turbulent degradation of horizontal vorticity. Observers often comment on the large numbers of small fire whirls to be seen in and around large fires. Although some of these are due to other mechanisms involving boundary conditions and introduced shear, others are properly regarded simply as a part of the fire turbulence. The earth's boundary layer and the air flowing into the fire have a predominantly horizontal natural structure of mean vorticity, and this has little immediate effect on the formation of fire vortices. However, at the high Reynolds numbers of natural flows there is also a coupled pattern of random vorticity (the turbulence) which interacts with the heat sources to produce local amplification, especially of those elements of vorticity which suffer more than average heating. Eddies of fire tur-

bulence will have random sense of rotation, but will tend to be perhaps an order of magnitude taller than they are wide, as they arise from the buoyant stretching of eddies which are probably stronger and hotter than average.

(5) A rather different buoyant mechanism for the local amplification of vorticity by the stretching of mean vortex tubes in plume-like flows has been demonstrated in tank experiments (Morton, 1963), but is likely to have only limited significance in fire whirl generation.

Vortex Generation near Boundaries.

Concentrated vortices may be formed also as a result of boundary effects and from the interaction of crosswise streams of fluid in an ambient stream.

(6) Whenever fluid is accelerated (or decelerated) along a retarding boundary under the action of a pressure gradient, vorticity is generated at the surface and diffuses out to form a boundary layer. On a plane boundary the vortex tubes of the boundary layer are parallel to the boundary, but vertically oriented or inclined

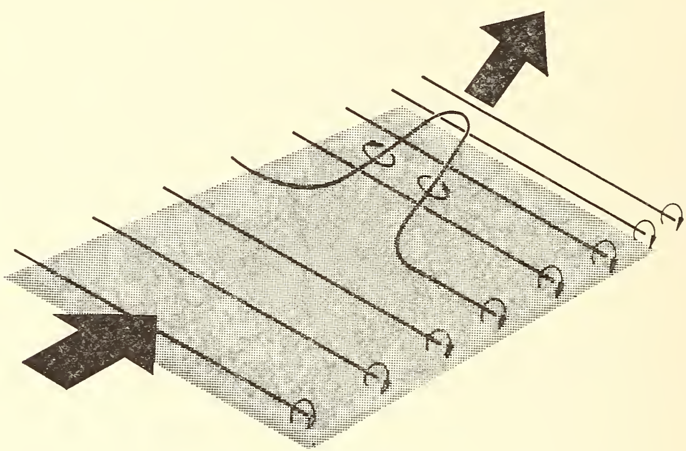

FIGURE 3

vortex tubes are formed on three-dimensional surfaces, and trailing vortices are certainly shed behind buildings and similar obstructions to the stream, and may be shed behind hills, in mountain passes and so forth.

(7) Even over a plane boundary it is possible, in principle at least, to produce vortex pairs locally by drawing up loops of vortex tube (shown schematically in Fig. 3; see also Emmons, 1965). Norbury, 1964, Küchemann, 1965, and Morton, 1966 have described an experiment which demonstrates the formation of such vortex pairs, but shows also that random ambient vorticity outside the extraction boundary layer frequently plays a dominant role, suppressing the formation of vortex pairs. He used an ordinary cylinder vacuum cleaner and tube to draw air over a horizontal plane boundary into the tube, mounted either parallel to the boundary or at right angles and directed towards it. A vortex pair formed just in front of the entry when the pipe was horizontal and close to the plane (Fig. 4) but the stability of this pair decreased as the pipe was raised and it was intermittently replaced by a single vortex with random sense of rotation due to disturbance

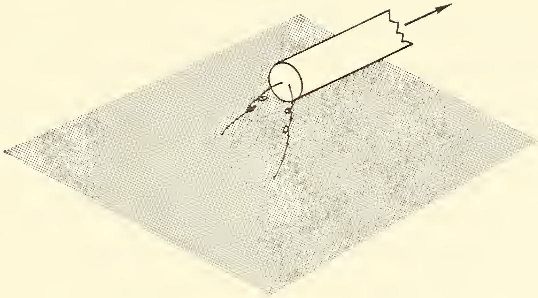

FIGURE 4

vorticity in the air above the plane (and single vortices could be caused readily by movements of the onlookers, producing vorticity that was convected towards the extraction pipe). The vortices required continuous maintenance and disappeared rapidly when the suction flow was stopped. With the pipe vertical, a vortex pair formed only when the entry was close to the boundary, and single disturbance vortices were the rule for larger separations.

(8) An apparently related, but in fact rather different phenomenon leads to the formation of vortex pairs in jets or plumes that are bent over by an ambient cross-flow. Under suitable conditions of wind and emission speed the smoke plumes from chimney stacks are seen sometimes to split into two quite definite side streams with relatively clear air between (Turner, 1960, especially Plate 1 which shows a plane view photograph of a split, bent-over buoyant plume). Vortex pairs are generated whenever a narrow stream is injected across a main stream or when buoyancy acts to generate transverse momentum in a coherent column of fluid inclined to the direction of the main stream. Fluid within the column moves primarily in the direction of the column axis nearby, while that outside the column moves principally with the main stream; thus there is an induced vortex layer on each flank of the inclined column, and these layers roll into internal vortex cores as indicated in Fig. 5. In extreme cases of stack emission all the emitted smoke passes into one or other of the cores, but normally the bent-over smoke plume preserves its coherence though showing clear evidence of its internal mean vortex pair structure by the

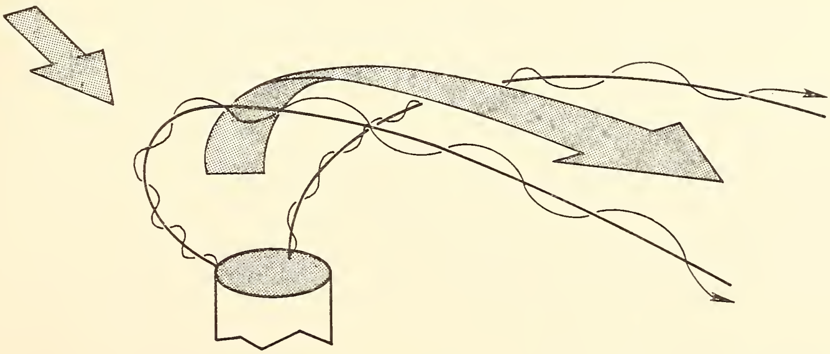

FIGURE 5

rolling motion of its flanks. The effect of a crosswind on a large fire plume will be to generate an internal vortex pair, the individual vortices of which will fluctuate somewhat in position, but will meet the ground roughly in the mean position of the sides of the downwind edge of the active fire area. The mean component of vertical vorticity in these regions is likely to be substantially larger than that elsewhere, and a majority of the medium to "largish" fire whirls may be expected to form there. Fire tornadoes require a higher degree of organisation of the vorticity field, and form only under exceptional conditions which usually require pre-generation of the appropriate vorticity to background levels that are substantially higher than those found in "bent-over fire plumes."

Ambient Instability.

The strength of a concentrated vortex depends obviously on the degree to which vortex tubes can be stretched, and its vigorous survival for any significant period of time depends as we have seen on preventing the low pressure zone of the core from "refilling" by axial inflow. Both the creation of strong vortices and their maintenance require strong and extensive buoyancy fields; and really large fire vortices appear to form only under conditions of strong insolation and unusually high ground temperatures, with the lower levels of the atmosphere in a state of unstable stratification. In such cases the fire vortex draws on the available potential energy of a much larger fluid volume, and serves to channel the release of this potential energy into its own kinetic energy of motion. The generation of fire vortices is, in fact, generally enhanced by conditions of ambient instability, although it is difficult to separate this effect from the general increase in burning rate of the fire as a whole under unstable conditions.

The Structure of Concentrated Vortex Cores

Problems involving the behaviour of concentrated vortices are mathematically difficult; relatively few complete solutions exist, and some of these are unsatisfactory. However a number of general statements on the physical structure of vortices can be made directly from the primitive equations or their integrated forms without need for formal solutions; and these are helpful both in understanding the behaviour of vortices and in formulating new problems correctly.

We shall restrict our attention to steady-in-the-mean, incompressible, axisymmetric-in-the-mean, turbulent vortices. Relative to cylindrical polar co-ordinates (r, θ, z) with origin fixed in position relative to a supposed "source" for the vortex the velocity has components $(u+u', v+v', w+w')$ where unprimed quantities represent ensemble averages and primes denote fluctuations, and the averaged equations of motion take the forms:

$$\underset{U/R}{r^{-1}(\partial/\partial r)(ru)} + \underset{W/Z}{(\partial w/\partial z)} = 0, \tag{1}$$

$$\underset{U^2/R}{r^{-1}(\partial/\partial r)(ru^2)} + \underset{UW/Z}{(\partial/\partial z)(uw)} - \underset{V^2/R}{(v^2/r)} = -\underset{P/pR}{\rho^{-1}(\partial p/\partial r)} - \underset{U'^2/R}{r^{-1}(\partial/\partial r)\langle ru'^2\rangle}$$

$$- \underset{C_{uw}(U'W'/Z)}{(\partial/\partial z)\langle u'w'\rangle} + \underset{V'^2/R}{(\langle v'^2\rangle/r)}, \tag{2}$$

$$r^{-2}(\partial/\partial r)(r^2uv)+(\partial/\partial z)(vw)=-r^{-2}(\partial/\partial r)(r^2\langle u'v'\rangle)-(\partial/\partial z)\langle v'w'\rangle, \tag{3}$$

$$UV/R \qquad VW/Z \qquad C_{uv}(U'V'/R) \qquad C_{vw}(V'W'/Z)$$

$$r^{-1}(\partial/\partial r)(ruw)+(\partial/\partial z)(w^2)=-\rho^{-1}(\partial p/\partial z)-r^{-1}(\partial/\partial r)(r\langle u'w'\rangle)-(\partial/\partial z)\langle w'^2\rangle,$$

$$UW/R \qquad W^2/Z \qquad P/\rho Z \qquad C_{uw}(U'W'/R) \qquad W'^2/Z \tag{4}$$

where capitals represent characteristic magnitudes for the variables in a slice of core with typical radius R and distance Z from the virtual source, and appropriate orders of magnitude have been entered under each term. Local scales

$$\{\langle u'^2\rangle^{1/2}, \langle v'^2\rangle^{1/2}, \langle w'^2\rangle^{1/2}\}\sim(U', V', W'),$$

$$(\langle v'w'\rangle, \langle w'u'\rangle, \langle u'v'\rangle)\sim(C_{vw}V'W', C_{wu}W'U', C_{uv}U'V'),$$

introduce profile-averaged correlation coefficients, such as

$$C_{vw}=\langle v'w'\rangle/V'W',$$

which are normally only weak functions of axial distance, z. Few values are available for the correlation coefficients, although these cannot differ greatly from 0.3 and will each be given this value in the following order-of-magnitude analysis.

The fluctuating part of the continuity equation,

$$r^{-1}(\partial/\partial r)(ru')+r^{-1}(\partial v'/\partial\theta)+(\partial w'/\partial z)=0, \tag{5}$$

$$U'/R' \qquad V'/R' \qquad W'/Z'$$

involves length scales R' and Z' for typical energy-containing eddies. Eddies in non-rotating tubulent jets are observed to be somewhat extended in the axial direction and have Z'/R' a little larger than 1, and R'/R rather smaller than 1. There have been several experiments on swirling* jets (including Rose 1962, Kerr and Fraser 1965, and Chigier and Chervinsky 1967) though these have not been carried far enough to produce detailed observations of the turbulent structure, and there appear to be no detailed studies of the turbulent structure of vortices* adequate for the present purposes. In a swirling jet it seems likely that there will be some constraint on radial disturbances in the interior where the circulation in paths r = constant *increases* with r, and enhancement in the outer sheath where circulation decreases with radius. For want of better experimental data it might be assumed that the *average* eddy structure across the profile in swirling jets (including contributions both from the inner zone where circulation increases with radius and from the outer annulus where it decreases again to zero) is comparable to that of non-swirling jets. The *profile-averaged* scales U' and V' would then be equal, and each slightly smaller than W'. For order-of-magnitude arguments, however, the differences between U', V' and W' are sufficiently small to be disregarded, and we shall take $U'=V'=W'$. Vortex core flows, with net circulation remaining non-zero, undoubtedly exert constraint on the radial fluctuations in particular, but again this will be neglected here for the order-of-magnitude analysis.

* We define a swirling core flow as having zero, and a vortex core as having non-zero net circulation.

The derivation of Eqs. (2) to (4) has already involved the assumption that viscous forces are small in relation to inertial forces for the mean motion. Hence, using for example the full equation for azimuthal motion:

$$\frac{\text{inertial forces}}{\text{viscous forces}} \sim \frac{VW/Z}{\nu V/R^2} \sim \frac{R}{Z} \frac{RW}{\nu} = \alpha \text{ Re} \gg 1, \qquad (6)$$

where $R/Z=\alpha$ is a measure of the semi-angle of spread for the core flow measured relative to its virtual source, and has typical values of 0.1 or less, and $\text{Re}=RW/\nu$ is a local Reynolds number for axial flow along the core. Under conditions such that the viscous forces may be neglected the Reynolds number will normally be large enough to ensure turbulence, although there are indications that the length scales for the turbulence in tornadoes (for example) are considerably smaller than they would be in a jet of comparable size.

Order-of-Magnitude Analysis

Commonly observed vortex and swirling core flows are *narrow* with semi-angle of spread

$$R/Z=\alpha \doteqdot 0.1 \ll 1,$$

and in all cases under consideration we can assume a large Reynolds number

$$RW= \text{ Re} \gg \alpha^{-1}.$$

The continuity equation (1) can be satisfied only if $U/R \sim W/Z$, provided that velocities sufficiently far outside the core are small enough to be neglected: hence

$$U \sim (R/Z)W \sim \alpha W.$$

The ratio of terms in Eq. (3) is, after some reduction,

$$1:1:\alpha^{-1}C_{uv}(W'^2/VW):C_{vw}(W'^2/VW),$$

where we substitute W' as the scale appropriate also to U' and V'. Although the two convective terms are comparable, the latter of the two turbulent transport terms is an order of magnitude smaller than the former, and may in some circumstances be neglected. Provided that the dynamical role of swirl is significant, this equation must reduce to a primary balance between convection by the mean flow and radial turbulent diffusion, with

$$C_{uv}W'^2 \sim \alpha VW. \qquad (7)$$

The terms of Eq. (4) are in ratio

$$1:1:P/\rho w^2:\alpha^{-1}C_{uw}(W'^2/W^2):W'^2/W^2,$$

with the penultimate term roughly half an order of magnitude greater than the final term. Swirling turbulent cores are driven axially by their excess of inertia over centrifugal pressure deficit except possibly in a region of limited extent close to the lower boundary, and the inertial terms of Eq. (4) will generally be significant and may be expected to be in balance with the main Reynolds stress term, so that

$$(W'/W) \sim (C_{uw}/\alpha)^{-1/2}. \qquad (8)$$

The pressure gradient forces cannot exceed the inertial forces in magnitude. In a strongly rotating core flow

$$P \sim \rho W^2, \tag{9}$$

and in general the magnitude of $P/\rho W^2$ provides a measure of the dynamical significance of swirl in the core.

Terms of Eq. (2) are in the ratio

$$\alpha^2 : \alpha^2 : V^2/W^2 : P/\rho W^2 : \alpha/C_{uw} : \alpha^2 : \alpha/C_{uw};$$

and if $\langle v'^2 \rangle$ is taken equal to $\langle u'^2 \rangle$ the three turbulent transport terms reduce approximately to $-\partial \langle u'^2 \rangle / \partial r$. In strongly swirling cores $P \sim \rho W^2$ and the primary balance is between the radial pressure gradient force and the centrifugal force, with

$$V \sim W;$$

and the contribution from turbulent transport, $-\partial \langle u'^2 \rangle / \partial r$, is smaller though by no means negligible. It should be noted particularly that V cannot exceed W in order of magnitude. As the degree of swirl decreases, the effect of turbulent transport increases in relative importance up to the state in which

$$V^2/W^2 \sim P/\rho W^2 \sim \alpha/C_{uw}$$

and beyond this stage the role of the centrifugal pressure field in providing dynamical coupling between the azimuthal and axial velocity fields weakens progressively, with final decoupling when $V^2/W^2 :: \alpha/C_{uw}$ in weakly rotating flows.

Collecting the more important results of the order-of-magnitude analysis*:

(i) The axial (W) and azimuthal (V) velocity fields are very closely coupled, and must have comparable magnitudes in a strongly rotating core;

(ii) This coupling acts through the pressure field and is a consequence of axial variations in the centrifugal pressure-reduction arising from axial variations in the width of the core;

(iii) Strong vortices or swirling flows have also strong axial flow, except, perhaps, in the immediate neighbourhood of an axial stagnation point; and

(iv) The radial component of velocity is relatively small, so that most of the fluid entering a core must do so from an end.

Flow Invariants in a Swirling or Vortex Core

By integration of Eqs. (1), (3), and (4) over a section of the core, z = constant, we can obtain a set of gross transport equations and can deduce the invariants for different flow-types. We require for this the boundary conditions:

at $r=0$: $u=0$, $v=0$, w finite, $\partial w/\partial r=0$, p finite, $\partial p/\partial r=0$, Reynolds stress bounded;

as $r \to \infty$: $u \to 0$, $v \to 0$, $w \to 0$, $p \to 0$, $r^2 \langle u'v' \rangle \to 0$, $r \langle u'w' \rangle \to 0$.

From Eq. (1),

$$(d/dz) \int_0^\infty \rho r w \, dr = -(\rho r u)_{r=\infty};$$

* A modified version of this and the following section have been given since the Canberra Mass Fire Symposium, in Morton, 1968.

thus the rate of increase of mass flux with axial distance is equal to the mass entrainment or radial inflow from large distances. All turbulent core flows exhibit entrainment in the sense that neighbouring ambient fluid gains axial momentum by diffusion, is accelerated into the core, and is replaced by more distant ambient fluid driven inwards by the weak external pressure field generated by the acceleration of fluid into the core. Provided that the circulation at (radial) infinity is bounded, the asymptotic effect of the jet at large radial distances is effectively that of some distribution of sinks along the axis of symmetry, and hence the asymptotic radial inflow velocity in an otherwise still and uniform environment must be $O(r^{-1})$, so that $(ru)_{r=\infty}$ is finite and is generally a function of z. In cases where the circulation increases continuously with radial distance for considerable distances the radial motion is further inhibited (as can be seen by conservation of angular momentum arguments) and fluid entrained into the core must be fed by an annular flow from top and bottom of the concentrated vortex; such flows from the basis of the vortex chamber. Thus *the mass flux along a rotating core is monotone increasing with axial distance except in a rotating environment.*

Integration of the r-moment of the azimuthal momentum Eq. (3) yields

$$(d/dz)\int_0^\infty \rho r^2(vw+\langle v'w'\rangle)\,dr=-(\rho r^2uv)_{r=\infty}, \tag{10}$$

where the right-hand term $\{\rho vr^3\, d(v/r)/dr\}_{r=\infty}$ representing viscous stress at infinity has been omitted with other viscous terms. The term on the right is proportional to the product of the entrainment flux $-(2\pi\rho ru)_{r=\infty}$ per unit length of core and the circulation $(2\pi rv)_{r=\infty}$ measured round the core. Thus the flux of angular momentum by a rotating core flow (due primarily to convection by the mean flow and slightly to longitudinal turbulent diffusion) is independent of axial distance, z, and hence an invariant of the flow only if $-(\rho r^2uv)_{r=\infty}$ vanishes; as the entrainment flux $-(2\pi\rho ru)_{r=\infty}$ is generally non-zero, we see that *only when the circulation at infinity vanishes is the flux of angular momentum along a core flow constant.*

Finally from Eq. (4),

$$(d/dz)\int_0^\infty \{\rho w^2+\rho w'^2+p\}r\,dr=-(\rho ruw)_{r=\infty}$$
$$=0$$

as ru is finite, and $w\rightarrow 0$ as $r\rightarrow\infty$. Hence,

$$\int_0^\infty (w^2+\langle w'^2\rangle+p/\rho)r\,dr=F/2\pi\rho, \tag{11}$$

$$W^2R^2 \quad W'^2R^2 \quad PR^2/\rho \qquad F/2\pi\rho$$

and the flow force F, comprising the total axial momentum flux and centrifugal pressure, is a flow invariant; orders of magnitude are entered under each term.

Thus in rotating core flows:

(i) The axial mass flux is monotone increasing, except in the case of flows $\mathrm{Ro}\ll 1$ dominated by ambient rotation when it is invariant;

(ii) The flow force (which is a gross effective axial force) is always an invariant of the flow, provided that there is no significant axial component of ambient motion; and

(iii) When the outer circulation, $K_\infty = (2\pi rv)_{r=\infty}$, is zero the axial flux of angular momentum is zero, but the outer circulation itself (and not the angular momentum flux) is the corresponding invariant when $K_\infty \neq 0$.

Some discretion is required in assessing the value of $K_\infty = (2\pi rv)_{r\to\infty}$. The vorticity of a fire devil is at least five-orders-of-magnitude greater than that of the earth's background rotation, but if we were to take r sufficiently large the contribution to K_∞ from the background rotation could be made to exceed the direct circulation of the fire devil by an amount as large as we please. However, the behavior of a small fire devil is probably totally unaffected by the rotation of the earth, and its rotation is unlikely even to arise directly from the earth's background rotation. Indeed, r should be interpreted more or less as an *inner* co-ordinate for a narrow core flow, and $r\to\infty$ does not imply that $r/z\to\infty$, but merely that r is sufficiently large to include the essential parts of the core; and the Rossby number characteristic of the constraint due to ambient rotation may best be taken in the form (disturbance vorticity)/(ambient vorticity). With this interpretation, when $K_\infty = (2\pi rv)_{r=\infty} = 0$,

$$\int_0^\infty r^2(vw + \langle v'w' \rangle)\,dr = G/2\pi\rho, \tag{12}$$

$$R^3VW \quad R^3C_{vw}W'^2 \quad G/2\pi\rho$$

where G is the constant flux of angular momentum. Both the flow force F and the angular momentum flux G are invariant in a core flow with zero net circulation, and this will probably be true for at least some fire whirls occurring naturally. We have shown already that for strongly rotating core flows $P \sim \rho W^2 \sim \rho W'^2$ [Eq. (9)], and hence from (11)

$$R^2W^2 \sim F/2\pi\rho;$$

and from (12)

$$R^3VW \sim G/2\pi\rho.$$

Thus both the flow force F and angular momentum flux G must be specified to define a swirling core embedded in an irrotational (or almost irrotational) environment, and

$$V/W \sim G/RF.$$

G/RF is a local non-dimensional parameter, termed the *swirl number*, which characterises the effect of axial rotation on swirling core flows; it decreases as the core radius increases, and as the core thickens the effect of rotation diminishes progressively; and the angular momentum flux cannot appreciably exceed the product of core radius and flow force. The attempt to increase the role of swirl in, say, a swirling jet leads to axial stagnation with a corresponding jump in radius which serves to reduce the dynamical effect of the swirl (Morton 1968).

Although the vorticity from which large fire whirls breed may well have originated in the rotation of the earth and its atmosphere, it is important that we emphasize that fire whirls of all sizes are high Rossby number flows. Thus the model discussed by Turner (1966) in which both vortex and return flow are restricted within a cylinder whose radius (which is less than that of the rotating tank) is determined by the Rossby number (which is small) cannot apply to fire whirls. However, Turner's emphasis of the roles of upper and lower boundaries is important and in some measure relevant to all kinds of concentrated rotational cores.

A more common situation is likely to be one in which fire whirls have finite circulation $K_\infty \neq 0$, and G is then no longer invariant but is a function of distance along the core. Instead,

$$(rv)_\infty = K_\infty/2\pi \qquad (13)$$

$$RV \qquad K_\infty/2\pi$$

is invariant, and from the scales for Eqs. (11) and (13) we now have

$$V/W \sim K_\infty/(2\pi F/\rho)^{1/2}.$$

An important difference is that, whereas the ratio of azimuthal to axial velocity in a swirling core varies as R^{-1}, this ratio is invariant in a vortex core, as are K_∞ and F separately. If, however, the vortex core is one of a "pair," with equal strength but opposite sense of rotation, the magnitude of the circulation for each core separately will remain constant only until vorticity diffuses to the bisecting plane of symmetry and will then decrease continuously with increasing time because of interdiffusion of "positively" and "negatively" oriented vorticity.

Vortex Interaction with Boundaries

The pressure field in a free and strongly rotational core is in approximate centrostatic balance with the centrifugal field of rotation, and the core acts almost like a "pipe" to transfer flow force. If the core "terminates" at a boundary, an end-wall-boundary-layer is formed of fluid retarded by end-wall-friction, and this retarded fluid cannot sustain the radial pressure gradients transmitted to it from the free core. Thus balanced flow is impossible near the wall, and fluid in the wall boundary layer is accelerated inwards and spirals towards and into the main core, along which it flows. The inflow rate is limited by viscous stress at the boundary, however, and for this reason strong rotational cores can suffer termination at a rigid boundary and receive quite limited rates of inflow. The boundary serves as a rather leaky termination, but makes possible the generation and continuing existence of strong rotational cores driven solely by upwards buoyant convection.

Just as the axial and azimuthal velocities are strongly coupled in the free core, so the radial and azimuthal velocities are strongly linked in the terminating boundary layer; and, of course, the radial velocity of inflow at the end-wall is closely coupled with the axial velocity within the core. It is precisely this close intercoupling that makes vortices so difficult to handle mathematically: for the inflow determines the axial flow in large measure, and the axial flow is tightly coupled with the azimuthal flow in the free vortex or swirling core, but the azimuthal flow very largely determines the structure of the end-boundary layer and hence the inflow which it passes. If at any point we break this chain of coupling we shall ultimately obtain a consistency relationship rather than a solution. Thus, in particular, we cannot impose the diameter of the free vortex in solving for the end-wall boundary layer (as many authors have done); for the end-wall plays a significant part in the force balance, which itself determines the diameter of the free vortex, and is in considerable measure responsible for the magnitude of the centrifugal pressure deficit in the core.

We are now in a position to dissect the flow field of a strong buoyantly-driven vortex above a rigid lower boundary, and a highly impressionistic and rather badly distorted representation is given in Fig. 6. The schematic subdivision contains the following regions for a flow with finite K_∞:

(1) The main vortex core is a narrow zone of diffusive flow in which the pressure suffers a centrifugal reduction, viscous or Reynolds stress forces are important, and axial and azimuthal velocities are (for a "strong" vortex) large and comparable in magnitude.

(2) A "stagnation point" region in which the inward flowing fluid from the terminating boundary layer is deflected into the core by pressure gradient forces. This is a region of inertial force/pressure gradient force balance in which Reynolds stress forces are relatively unimportant.

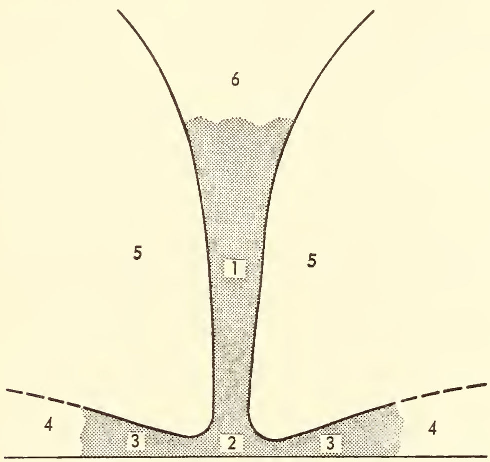

FIGURE 6

(3) The "terminating" or "end-wall" boundary layer consisting of a thin sheet of fluid which spirals into the core under the action of the unbalanced pressure forces. Reynolds stresses are important in this region (which has been drawn rather thick for display).

(4) As we move further out through the terminating boundary layer it thickens progressively and the Reynolds stresses diminish in importance until we merge into—

(5) Consisting of a region of inviscid flow under the influence of the vortex core and the sink-like effect of fluid being drawn into the ground boundary layer.

(6) The vortex core widens with height and merges into a region of strong buoyant motion in which Reynolds stress/viscous forces diminish in importance. The buoyancy in this region must be strong enough to prevent backflow which would "fill up" the core and destroy the vortex. It is not enough for buoyancy to act only within the concentrated core because it must effect a match between the core pressures and ambient pressure, and the centrifugal pressure reduction decreases only as the core grows in width.

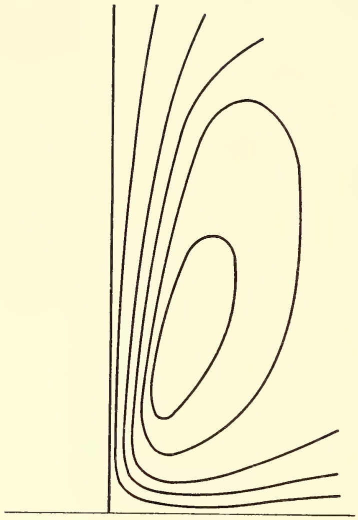

FIGURE 7

Figure 7 shows a possible field of vortex lines for the concentrated vortex of Fig. 6. Note that the circulation is shown first increasing with radius and then decreasing slowly with further increase of radius, a relatively common phenomenon.

Whirl Models and Microstructure

Many authors have written on vortex interaction with boundaries, on swirling and vortex plumes and on full models with ground interaction, but the results have so far tended to be disappointing and we do not have the space here to carry out an adequate analysis in this area. It may be sufficient to mention the treatment of Emmons and Ying (1967) for the fire whirl interpreted as a vortex plume without ground interaction; and that of Barcilon (1967) which, despite some weaknesses, does attempt to model the full problem of a whirl above a rigid boundary for dust devils.

The knowledge of flow microstructure is at present incomplete and may better be reviewed at a later time.

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Subject: I
Subjects: Aerodynamics; Fire whirls; Tornadoes; Vortices.

DUST EXPLOSION

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"The building and contents at this location were a total loss with no salvage possible." That statement appears frequently in insurance reports. In many instances an explosion or fire caused the destruction cited. The following are examples of such accidents:

(1) A pickup load of grain was dumped into the drive pit at an elevator and then legged to the bin-top. During that time an explosion occurred in which five people were burned and the elevator damaged.
(2) Employees were cleaning a radiant tube-type heater in an enclosed area when an explosion occurred. The explosion carried through the work floor and up the manlift shaft causing damage to the structure.
(3) A contractor was welding on the elevator leg when an employee took in a load of milo. As he attempted to leg it into a bin, an explosion occurred at the welding site, resulting in an explosion front going down the leg, flashing into and across the driveway to an adjoining elevator. Then an explosion started a fire in the mill killing two men and costing more than one million dollars' damage.

The list of firms damaged by explosion is long. Twenty-nine recent dust explosions were cited among grain processing firms. The combined loss was over three hundred thousand dollars. One firm listed eighteen locations where lives, buildings, and millions of dollars were lost. The explosions occurred at all hours, in all types of weather, and at various types of buildings in all stages of repair. Some buildings were firetraps, while others apparently were textbook cases of cleanliness and modern efficiency. However, dust was the common factor involved. Because of the hazards of working in a dust-laden environment, it is the economic and moral responsibility of management and employees to understand the destructive capabilities of dusts.

In this paper, dust and dust explosions are discussed as follows:

1) Dust and dust cloud definitions
2) Dust cloud formation
3) Parameters of dust cloud combustion
4) Flammability of dust clouds
5) Industrial causes of dust explosions
6) Preventing industrial dust explosions

Definition of Dust and Dust Cloud

To understand the mechanism of a dust explosion, dust should be defined. Mill Mutual Fire Prevention Bureau[30] stated that dust is made of particles of organic and inorganic substances of various shapes, sizes, and weights. Cadle[10] pointed out that dust particles may vary in size, but have definite physical boundaries in all directions. Sussman[44] defined dust as a loose term applied to solid particles predominantly larger than colloidal particles and capable of temporary gas suspension. Greeg[23] stated that dusts are particles from 1 to 150 microns (micron = 0.001 mm) in diameter, falling or settling in an aerial disperse system.

Particles of 0.001 to 1.0 micron in diameter dispersed in gas form a cloud on which various laws of colloidal chemistry may be used. Shellenberger[43] stated that dust clouds are disperse systems in which the dispersion medium is air. Greeg[23] used the term aerosol to identify the systems.

In this paper, the word "dust" is used to discuss particles 0.1 micron or larger, and the term "dust cloud" is used when dust particles are suspended in a gas. Factors related to dust cloud formation and combustion, industrial causes of dust explosions, and industrial safety practices are discussed.

Factors Related to Dust Cloud Formation

Shellenberger[43] stated that aerosols, like other disperse systems, can be formed by dispersion or condensation, but dispersion is by far the most important method for forming dust clouds. Dawes[11] studied conditions under which dust deposit becomes unstable from exterior stress, and found three facts:

(1) Dusts can be piled into heaps that retain their shape as long as no external force greater than a certain minimum is applied.
(2) Dusts resist compression.
(3) Individual particles form into aggregates.

Dawes[11] inferred that frictional forces appear within the dust pile when two of the structural units or particles move relative to one another. The frictional forces exert both attractive and repulsive forces on the particles. Those forces affect the initial formation of a dust cloud.

Brown[3] pointed out experimental methods for dispersing dust into clouds and grouped them as follows:

1) Dispersion by an air stream passing over or through a bed of dust.
2) Dispersion by mechanical stirring in a vessel.
3) Dispersion by metered feeding in an air stream.

Orr and Dallavalle[39] used a sedimentation method for dispersing a dust cloud in determining particle size. The sample was placed in a recessed holder and blasted with a gas through a narrow conical slit into a settling chamber. In industry, aerosols are most frequently produced by disintegrating solids, as in an attrition mill.[43]

Parameters of Dust Cloud Combustion

Generally, any dust that will burn or oxidize readily and is fine and dry enough to form an aerosol in air can produce an explosion. Dorsett *et al.*[13] stated that a dust explosion is a rapid combustion of a cloud of particle matter in a confined or partially confined space where heat is generated at a much higher rate than it is dissipated. For a dust cloud to explode, the following conditions must be present:

(1) Dust concentration in a cloud must fall within certain limits.
(2) A portion of the cloud must be raised to its ignition temperature.

Theoretically, if combustion involves only oxidation, the strongest explosions are produced at a concentration with just enough suspended dust to consume all the available oxygen.[25]

Ignition of a dust cloud occurs only within definite limits of particle concentration.[7] The minimum dust concentration that will explode is reached when the heat evolved from ignition is insufficient to ignite adjacent particles and ensure continued combustion. The upper limit of concentration is found when there is so much present that the oxygen available is inadequate for continued combustion.

Equipment and experimental techniques for determining dust concentrations and dust cloud ignition limits are not standardized. Several factors account for conflict among published data: the problem of producing a uniform cloud, the importance of timing ignition with dust cloud formation, the variety of ignition sources, and the variation of samples.[24] Brown and Essenhigh[6] issued a report describing an apparatus that will create satisfactorily a dust cloud of known concentrations. Although the apparatus was used to study flame propagation, it also could be used to determine the limits of dust concentration at which ignition occurs in the cloud.

Brown[2] reported that starch, grain dust, wood dust, powdered sugar, cork dust, coal dust and some metal dusts are representative types of dust that will explode. Experiments were done in England to determine the minimum dust concentration necessary for ignition.[3] Minimum concentrations were calculated from the lowest weight of a specific dust sample that ignited in a vessel of known volume. Aluminum was found to ignite at a concentration of 0.037 g/liter, while magnesium powder ignited at 0.030 g/liter. The experimenter questioned his results for a uniform cloud could not be produced within the vessel. He suspected that primary ignition took place before the entire sample could be injected into the explosion vessel. A safety manual reported findings placing the lower concentration limit between 0.01 and 0.5 ounces per cubic foot, with the average being 0.02 ounces per cubic foot of air.[33]

Nagy[35] investigated the change in concentration limits when an inert powder was added to a dust cloud. Possibly the method used in his study can be used to evaluate and establish industrial concentration limits where combustible particles are found in suspension with inert materials. Such clouds may explode at concentrations other than those given by laboratory experiments using uniform particles.

For present industrial purposes the limits of concentrations expressed by investigators must be viewed as approximations and not standards. Burgoyne and Faulds[9] advised that in practice, it is probably unwise to consider non-explosive any cloud having a dust concentration more than 25 percent of that determined in the laboratory as the lower limit of concentration. An extensive list of minimum explosive concentrations for clouds was compiled for 220 agricultural dusts in an experimental environment by Jacobson *et al.*[28]

After dust particles are dispersed into a cloud formation within the limit of concentration necessary for an explosion, the following factors influence ignition and subsequent combustion of the dust cloud:

1) physical characteristics of the particles
2) temperature necessary for ignition
3) factors of flame propagation through the cloud
    (a) inert particles
    (b) moisture
    (c) O_2 concentration

The meaningful physical characteristics of a potentially explosive dust cloud are its composition, affinity for oxygen, heat of combustion, volatile matter, ash and moisture content, specific heat, and particle size. The effect of volatile matter is particularly evident in coal dusts. The low volatile content of anthracite coal is the chief cause for its low explosibility.[24]

The size, shape, and surface structure of dust particles influence their ability to ignite. However, it is difficult to establish limits for each factor. While it is recognized that fine dusts are very hazardous, an experiment by Hartman[24] showed that when finely divided coal dust is used, particles as large as 800 microns in diameter can contribute to the explosion. Using corn starch, Nagy *et al.*[35] found the maximum diameter of a reacting particle during an explosion was approximately 3810 microns. Up to a point the explosibility of a combustible dust increases with a decrease in relative particle size, for the fine particles of dust exhibit a higher specific surface upon which a reaction may take place. Fine particles also disperse more thoroughly with the available oxygen, resulting in a faster rate of vaporization and oxidation. This in turn increases the explosibility of a cloud due to the greater volume of oxygen absorbed per unit weight by the dust. The electrical capacitance per unit weight of fine dust is greater than that of coarse dust, also increasing the explosibility of a cloud.

The ignition temperature of a cloud may be defined as that temperature at which the reaction rate becomes critical enough to self-propagate the combustion process. Brown and James[7] described combustion mechanism of single particles in three stages: (1) the preignition heat absorption, (2) ignition and combustion of the volatile matter evolved, and (3) the combustion of the remaining particles. However, their studies used only fossil fuel particles. In a comparison study between the combustion mechanisms of liquid and solid aerosols, Essenhigh and Fells[20] noted that the mass burning rates and times were similar in both systems. The reaction surfaces were believed to be in different physical positions. For the liquid drop, combustion took place at a definite distance from its surface, while for the solid particle combustion took place either on the surface or within the particle's interior. That property of internal combustion by a solid particle may explain why industrial accumulations of dust can occasionally smolder for long periods of time without bursting into visible smoke or flame. Experiments conducted on agricultural dusts disclosed that a change in the average particle diameter affected not only the minimum energy needed for ignition, but also the rate of pressure development as the explosion progressed.[28]

The mechanism of ignition is not completely understood. The predistillation theory is that heat builds up in some particles within the cloud.[24] As continued heat is applied, the volatiles in the particle begin to distill off and mix with air. This combination of volatiles and air forms the site of primary ignition in a cloud. The combustion continues after the volatiles are exhausted by consuming the remaining solid particles. However, some dusts will ignite at temperatures below the ignition temperature needed for combustion of gases given off by distillation. Another theory is that ignition initiates a direct surface oxidation of the particle.[27] That seems to agree with ideas of Essenhigh and Fells[20] about the position of combustion on a particle. According to the thermal theory, ignition occurs when a dust and air mixture is heated until its oxidation produces heat faster than heat is lost to the surrounding environment.[24] That is followed by continued self-heating that leads to sustained combustion.

Radiation can take an active role in igniting a dust cloud.[24] It has also been suggested that under some conditions the pressure wave of an explosion can lead to a sort of dynamic shock ignition of a cloud. However, technically speaking, that is a thermal ignition due to the heat of compression. Electrical ignition can also occur, but that depends largely on producing sufficient concentrations of charged particles resulting from electronic collisions. That in turn depends upon the presence of ions or ionized particles in the cloud.

Absolute values for the temperature or energy necessary to ignite a particle can be established in laboratory experiments. However, the same particles suspended in a cloud can and do ignite at different values.[19] Thus to accept experimental ignition values as definite guides in an industrial situation could have disastrous consequences.

Once ignition occurs the remainder of the explosion propagation takes place as flame propagation through the cloud. McCann[29] related a graphic description of flame propagation through a cloud. As the dust cloud settles over the flame, heat ignites the particles of dust next to the flame. As they burn, they in turn give off heat and ignite adjacent particles. The flame travels up through the dust cloud. Essenhigh[16] referred to the transfer of heat from the flame front forward to the unburnt portion of the cloud as the thermal theory of propagation.

Tests in which a flame can be observed propagating through a dust cloud offer a convincing example of the explosion hazard and a qualitative indication of available force during the reaction. The flame front has an expansion wave in front of it.[15] The wave agitates the dust particles in suspension. Without agitation the dust would settle and flame propagation would fail. Measurements of flame speed and ignition temperature have been made.[21] Generally, measurements from small-scale laboratory equipment have no value in predicting behavior in an industrial situation. The values obtained in the laboratory depend entirely on the configuration of the equipment and the source of ignition.[7]

The addition of inert powder or moisture to a cloud results in an almost linear relationship between rates of pressure development, burning and flame propagation.[35] The larger the quantity of material or water added, the slower the reaction.

McCann[29] stated that humidity contributes strongly to the dust explosion hazard. According to Hartmann,[24] highly hygroscopic dusts can absorb sufficient moisture from humid air to agglomerate. Agglomerates can settle out and decrease the explosion hazard, while others may disperse and form a cloud. In a humid environment certain metal particles form oxides on their surface, and others generate sufficient heat to ignite. Experiments on coal, starch, and other dusts have shown moist dusts explode violently.[26,24] On occasion additional small amounts of moisture in a cloud can increase its explosive violence.[35] Hartmann and Nagy[26] also pointed out that a high relative humidity in air is capable of conducting an electrical current. That could allow a charge to seek ground along the walls in an explosion space, decreasing the possibility of spark ignition. The above studies indicate that humidity affects industrial dust explosions, but to what degree and how is not clear.

The ignition of a dust cloud and the severity of combustion are affected by the cloud's oxygen content. Ignition temperatures will increase as the oxygen content is reduced.[25] Diluting a cloud with noncombustible gases or inert particles will reduce its oxygen content and retard flammability.[25,17] The lower explosion limits for a dust suspended in air (20.9% oxygen) were found to be similar to those suspended in an atmosphere of 100 percent oxygen.[25] Both systems contain ample oxygen necessary for complete combustion of the cloud. As the partial pressure of oxygen drops, the rate of diffusion toward the particles decreases. In an atmosphere containing less than the ideal ratio of solids to gas any reduction of oxygen will retard combustion and heat generation.[25] Nagy *et al.*[35] showed that the maximum rate of pressure rise decreased almost linearly with decreases of oxygen. Oxygen concentration varies slightly with dust concentration, and the lowest possible level is two to five times the stoichiometric mixture.[12] Dorsett *et al.*[13] developed a reproducible method for determining the oxygen concentration of a cloud.

Flammability of Dusts

Some of the investigations of dust explosions, etc. have been studies intended to identify flammable dusts in industry. Five such studies are discussed in this section.

According to Brown,[3] Wheeler investigated the flammability of dusts after two serious explosions in 1911, using a horizontal glass cylinder for an explosion chamber. Dust was placed in an injection tube that projected into the chamber. A blast of air then dispersed the dust into the large tube where it was ignited by a platinum coil. If the dust ignited, the temperature of the coil was reduced and the sample retested. This was repeated until two temperatures were obtained, differing by 19 degrees; at one temperature the dust ignited, while at the other the dust failed to ignite. As a result dusts were placed into one of the following three classes of flammability:

1) Dusts that flame readily
2) Dusts that flame readily but need additional energy to propagate
3) Dusts that will not flame under industrial conditions

The experiment was repeated later with minor variations.[3] The investigator found that the tests did not provide conclusive answers for the following questions:

(1) Will the sample cloud ignite and propagate?
(2) At what density is the cloud explosive?
(3) How much pressure is developed by the explosion?

Dorsett *et al.*[13] reported a description of equipment and test procedures used to study the explosibility of dusts. The primary tests concern ignition temperature, minimum explosive concentration, pressure and rates of pressure rise. The ignition temperature, determined in a Godbert–Greenwald furnace, was the minimum furnace temperature at which a flame appeared at the bottom of the furnace in one or more trials out of four.

Minimum explosive concentrations were determined in the Hartmann apparatus using an induction spark igniting source instead of the normal timed condenser discharge spark. The explosion had to break a paper diaphram. If propagation occurred for a given weight of dust, that quantity was reduced by 5 mg. This continued until propagation did not occur on four successive trials. The lowest weight at which a flame propagated was used to calculate the minimum explosive concentration limit.

The minimum electrical energy for ignition was determined on the Hartmann apparatus. The minimum energy for ignition was obtained by measuring the least electrical current across a gap, producing flame propagation four inches or longer in the chamber.

Limiting oxygen concentration studies were conducted with premixed gases fed into a modified Godbert–Greenwald furnace. The atmospheres were diluted with carbon dioxide or nitrogen until ignition ceased.

Pressure and rates of pressure rise developed by a dust explosion were determined in a closed steel Hartmann tube. The explosion pressure was measured by a manometer or electronic transducers. Maximum pressure plus the average and maximum rates of pressure rise in an explosion were determined from pressure-time records. As a result of the tests described above, the sample materials were placed into four categories:

	Example
(1) No dust explosion hazard	Anthracite coal
(2) Slight hazard	Coffee
(3) Moderate hazard	Pittsburgh coal
(4) Severe hazard	Aluminum powder

Jacobson *et al.*[28] evaluated the explosibility of 220 agricultural dusts in air using the equipment and procedures previously described. To facilitate evaluation of the explosibility of dusts and to assign a numerical rating to the relative hazard, three empirical indexes were developed: ignition sensitivity, explosion severity, and the index of explosibility. The indexes are dimensionless quantities assigned a numerical value of 1 for dusts equivalent to the standard Pittsburgh coal. Hazards were further classified as weak, moderate, strong, or severe.

Dust explosion data for 73 chemical compounds and mixtures, 29 drugs, 27 dyes, and 46 pesticides were published by Dorsett and Nagy.[14] The equipment and methods used to collect the data were similar to that used by Jacobson and his colleagues. The chemical mixtures consisted of two or more primary chemicals. The drugs were mostly chemical compounds, while the remainder were animal, vegetable, or fermentation products with medicinal value. The dyes were mostly coal-tar derivaties. The pesticides tested were insecticides, miticides, herbicides, fungicides, and bactericides. Most of the data were derived from dusts passing through a number 200 sieve. Duplicate samples were not run on the majority of materials. Chemical formulas having C_6 or higher showed the greatest dust explosion hazard.

An extensive list of flammability data taken from an investigation of agricultural dusts and from an investigation of chemicals, drugs, dyes, and pesticides appear in the Appendix.[28,14] From an industrial point of view, the most valuable information in the tables are the ignition temperatures and rates of pressure rise. Some ignition temperatures for common dusts are low. For example, wheat starch ignites at 380°C. Also note that while rates of pressure rise are not factors of flammability, they are an important result of combustion. The sample of wheat starch exhibited a rate of 8500 psi/sec rise in pressure. This is the destructive force which in seconds can reduce an industrial plant to rubble.

Industrial Causes of Dust Explosions

In many instances the exact cause of a dust explosion cannot be determined because the evidence is destroyed.[24] Olson[38] reported that the majority of dust explosions between 1860 and 1956 occurred in the collector or bin of a dust-collection system. The insurance loss reports indicated that explosions often occur in areas where machinery is being operated. Within a given area dust explosions may be ignited by the following possible sources: (1) open flames, (2) hot surfaces, and (3) electrical discharge.

Open flames may occur due to foreign material entering a production area. For example, matches, cigarettes, metal and other spark-producing materials ignite dust clouds easily. Other flames that may ignite a dust cloud include: flames from heating or drying equipment operated by oil or gas, gas lights and solid fuel emergency flares. Gas welding equipment, boiler backfires, and breaks in oil or fuel lines may also ignite a dust cloud.[33]

Any surface that is hotter than the lowest ignition temperature of a dust may ignite a cloud. Such surfaces may occur in a production facility from overheated bearings, belt slippage on pulleys, and unshielded light bulbs.[24] Metal particles from machining, grinding, riveting, or sanding operations may have elevated surface temperatures sufficient for igniting a dust cloud. Friction clutches, screw conveyors, and electrical dryers may contain surfaces hot enough for dust cloud ignition.[37] It is also possible for bin surfaces to be heated by the spontaneous ignition of feeds, grains, or hay.[32]

A spark triggers an explosion in an internal combustion engine. The same process of ignition is possible in a production facility. Park[40] found evidence of static electricity in wheat being discharged from bucket elevators. Hartmann[25] reported that the human body may carry as much as 10 millijoules of energy, in many instances more than enough to ignite a dust cloud. Olson[38] reported that grain dusts moving through pneumatic systems generate charges of over 20,000 volts. If sufficient resistance is present, enough electrostatic charge may be accumulated to cause ignition of a dust cloud. Other possible electrical sources of industrial dust explosions are sparks and arcs from motors, switches, fuses, short circuits, and welding equipment. Significantly, out of more than 100 recorded dust explosions only $2\frac{1}{2}$ percent can be attributed to electrical equipment.[1]

Preventing Industrial Dust Explosions

Recognizing the importance of preventing loss of life and property due to dust explosions has prompted many investigations and experiments. Consequently, data are now available so that the problem is not so much lack of prevention, as amount of prevention. Industry must seek a point in its explosion prevention investment that offers adequate protection without excessive capital expenditure.

Preventive measures in industry are directed principally at reducing the formation and dissemination of explosive dusts throughout plants and mills.[24] Eliminating all possible sources of ignition from hazardous areas must be attempted in building construction, type of equipment used, daily in-plant maintenance schedules, and employee safety practices.

Buildings should be constructed to segregate dangerous dust-producing processes. Dusts may be thrown into suspension by mechanical agitation or by air currents. Consequently, the problem of dust control is of primary importance. The basic function of a dust control system in a plant is to prevent dust from escaping from machines into the atmosphere.[31] There must be a movement of air where dust is escaping from machines. Reducing pressure within the machines can stop escaping dust, but that is impractical; isolating the machine will prevent the dust from dispersing beyond that particular area.[34]

Methods have been investigated for preventing excess damage to structures by dust explosions. Nagy *et al.*[36] reported on experiments to determine the relative effectiveness of an unrestricted vent and 22 different types of closures. The closures were constructed of paper, cloth, metal foils, hinged doors, hinged panels, and glass panes. The idea was to vent the explosion out of the structure through ducts, blow-out walls or rupture disks. The data indicated that explosions with high pressures were difficult to vent. Restricting the vent with any type of diaphragm, hinged panel or glass pane increased the maximum explosion pressures produced in the test chamber. Pressure-relieving capacities of diaphragms decreased as the diaphragm thickness increased and were almost inversely proportional to the static-bursting strengths of their material. Hartmann and Nagy[27] obtained additional information on venting principles and construction. A single vent in a vertical wall was used to limit the explosion pressures developed. When vents of various shapes were investigated, it was found that frequent necessary interposition of ducts between vents and the outside atmosphere increased maximum pressures within the system. Secondary vents in the system increased the overall effectiveness of the primary duct when located near the potential source of an explosion.

Brown and Wilde[8] reported on pressure relief through hinged doors. A hinged door was placed at the end of a 50-foot tube 30 inches in diameter. The resulting data indicated the door did not restrict the escaping pressure. Another study investigated a method that used an explosion detector and quick-closing duct valves to isolate the spread of a dust explosion.[5] With a violent explosion the detector reacted and triggered the valves closed. But when the explosion was weak, the detector did not react fast enough to close the valves.

Brown and Curzon[4] investigated the effectiveness of various explosion vents in a fuel-pulverizing mill. They found that bursting panels of weak material or a reduction of relief area in the mill increased the violence of the explosion. A solution was obtained by placing a simple plate valve over the open mill vent. Two types of deflectors were used successfully in diverting flame and effluent gases without raising pressures in the vents.

In considering electrical equipment for use in a potentially explosive environment, the primary requirement is that all circuits be isolated from the hazardous atmosphere. All switches, fuse and terminal boxes, starting rheostats, and wiring should be enclosed. Enclosed motors should be of the brushless type. Sauerteig[41] advised that all static-producing equipment be grounded.

Maintenance programs are an invaluable aid in reducing the incidence of dust explosions. It is important to impress employees with the necessity for good plant housekeeping, which includes frequent cleaning and good ventilation. Scheduled cleaning programs reduce the possibility of accumulated dust becoming a hazard. Sax[42] advised that the use of compressed air by employees to remove dust from equipment should be forbidden because a jet of air is an efficient method for creating a dust cloud. Regular machine maintenance reduces bearing failures that can lead to the ignition of a dust cloud.

In the final analysis, it is the adoption and use of recommended safety procedures that reduce the explosion hazard. The experience of Farmers Elevator Mutual Insurance Company[22] prompted them to recommend that all elevator legs in grain and milling properties be vented properly. Olson[38] advised companies to educate their employees as to the dangers of dust explosions and methods to prevent them. The liability caused by humans working in any hazardous environment can be reduced if a company will aggressively promote and enforce established safety measures.

The company that initiates a safety program will discover many organizations to aid and advise it concerning all phases of plant design, construction, and operation. The Engineering Service Department of Mill Mutual Fire Prevention Bureau aids industry with complete manuals and bulletins concerning plant design, maintenance and safety practices. The same type of service is offered by Farmers Elevator Mutual Insurance Company of Des Moines, Iowa. Any state extension service will aid business owners in establishing safety practices. Departments and Bureaus of the Federal Government publish a multitude of safety manuals that may be obtained from the Government Printing Office in Washington, D.C. Assistance from the above sources enables any businessman to establish a sound and economical safety program for his warehouse or factory.

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Section: G
Subject: Dust explosions

ABSTRACTS AND REVIEWS

A. Prevention of Fires and Fire Safety Measures

Chambers, E. D. (Joint Fire Research Organization, Borehamwood, England) "Worcester City and County: Effect of Firemen's Advice Scheme on Dwelling Fire Frequency," *Joint Fire Research Organization Fire Research Note No. 773* (1969).

Sections: A, K, L
Subjects: British brigades; Cost benefit; Dwelling fires; Fire prevention; Firemen's advice, Worcester

Author's Summary

For an area where firemen carry out a house-to-house visiting scheme, the relative frequency of fires in dwellings is compared with the national average. Over ten years a reduction of one-third appears to have been achieved.

Daxon, W. N. (Joint Fire Research Organization, Borehamwood, England) "Lancashire County Fire Brigade Domestic Fire Hazards Removed after Advice from Firemen," *Joint Fire Research Organization Fire Research Note No. 771* (July 1969).

Sections: A, K, L
Subjects: Domestic fire hazards; Fire brigades; Fire prevention; Firemen's advice, Lancashire; Publicity

Author's Summary

An indication of the reactions of householders to visits by firemen giving advice on fire prevention in their homes and their willingness or otherwise to cooperate, has been obtained. A high proportion of householders were prepared to receive visits and over half of the hazards observed by the firemen were removed before a second visit was made.

Siconolfi, C. A. (Durez Division, Hooker Chemical Corporation, North Tonawanda, New York) "Fire Retardance in Chemical Process Ductwork," *Fire Technology* 5, 217–224 (1969)

Section: A
Subjects: Chemical processing; Ductwork retardance

Reviewed by G. A. Agoston

Glass-fiber-reinforced polyester is being widely used in the construction of various types of process equipment. For these the outstanding advantages of corrosion resistance and ease of construction are well established. The danger, however, of fire spread through chemical process duct systems fabricated from non-fire-retardant resins demands attention.

A series of tests has been conducted to compare during typical operation the flammability of air ducts made from non-fire-retardant polyester and from two fire-retardant polyesters, Hetron 92TG and Hetron 197–3, both with 5 percent antimony oxide (products of the Hooker Chemical Company). The ducts had a 10-in. inside diameter, a $\frac{1}{8}$-in. wall thickness, and a length of 75 in. A hole was provided near the upstream end to permit the insertion of an oxy-acetylene torch for ignition of the wall interior. Air was blown through the ducts at rates of 300 and 3000 fpm.

When non-fire-retardant polyester was employed, ignition was produced quickly at 300 fpm. The torch was removed after 1 min and the air rate was simultaneously increased to 3000 fpm. Burning continued until the resin was completely consumed $2\frac{1}{2}$ min later. Flame had appeared initially along the top of the duct in 30 sec after the removal of the torch and the duct had collapsed 1 min later.

The two Hetron resins did not become ignited when the test procedure was followed. Within 15 sec after the removal of the torch, there was no evidence of smoke or flame. While still at 3000 fpm the torch was also used to cut holes into the ducts, but again ignition was not accomplished.

Kovalo, J. C. (Goodyear Atomic Corporation, Portsmouth, Ohio) "An Evaluation of Sprayer Mist Fire Hazards," *Fire Technology* 5, 233–236 (1969)*

Section: A
Subjects: Fire hazards; Hazards; Mist fires; Sprays

Does the act of recoating wire mesh type air filters while they are in place significantly increase the fire hazard? Tests conducted by the author indicate that the operation can be performed in relative safety if the proper lubricant is used.

* Abstract from *Fire Technology*. By permission.

Rogowski, Z. W. (Joint Fire Research Organization, Borehamwood, England) "Flame Arresters as Barriers against Hot Metal Particles," *Joint Fire Research Organization Fire Research Note No. 783* (September 1969)

Sections: A, N
Subjects: Electrical equipment; Flame arresters; Metal particles; Particle incendive; Sparks

Author's Summary

Crimped ribbon flame arresters mounted on a 9-liter vessel exposed to arc discharges obtained by fusing of copper wires within the vessel, prevented the ignition of 4 percent propane–air on the outside of the vessel. However, a 6.5 percent ethylene–air mixture and a 3.4 percent diethyl–ether–air mixture were ignited by the hot metal particles produced by the discharge.

The particles produced by fusing of copper wires were, however, safely and easily contained within reinforced insulating sleeving, providing it was strong enough to withstand the transient pressures and the temperatures generated during fusing of such wires.

Palmer K. N. and Rogowski, Z. W. (Joint Fire Research Organization, Borehamwood, England) "The Protection of Equipment with Flame Arresters. Part III. Performance of Arresters with Ethylene–Air Flammable Mixture," *Joint Fire Research Organization Fire Research Note No. 756* (July 1969)

Sections: A, N
Subjects: Etyhlene-air; Protection; Venting arrests

Authors' Summary

Experiments were carried out evaluating the performance of flame arresters when fitted to cubical enclosures. Data are presented giving simple correlation between the area of flame arrester or vent and the maximum explosion pressure in small cubical vessels using 6.5 percent ethylene–air explosive mixture. The effect of simple obstacles on the maximum explosion pressure was also investigated. These results are compared with the results obtained in the past, using propane–air mixtures.

Palmer, K. N. and Rogowski, Z. W. (Joint Fire Research Organization, Borehamwood, England) "The Protection of Equipment with Flame Arresters, Effect of Variation of Gas Composition and Contents," *Joint Fire Research Organization Fire Research Note No. 784* (October 1969)

Sections: A, N
Subjects: Electrical equipment; Flame arresters; Gas composition; Protection

Authors' Summary

Further evaluation has been made of performance data for the use of flame arresters for protection of electrical equipment. A correlation is presented between the fundamental burning velocity of the flammable mixture and the maximum explosion pressure for both propane–air or ethylene–air mixtures.

The effect of contents of various vessels on the maximum explosion pressures developed was studied.

Rogowski, Z. W. (Joint Fire Research Organization, Borehamwood, England) "Field Trials to Assess the Blockage of Arresters by Atmospheric Pollution," *Joint Fire Research Organization Fire Research Note No. 786* (October 1969)

Sections: A, N
Subjects: Arrester blockage; Atmospheric pollution; Flame arresters

Author's Summary

Tests have been carried out to evaluate the blockage of flame arresters caused by atmospheric pollution. A daily throughput of air of 143 m^3 (4500 ft^3) through six arresters 2.9 cm (1.15 in.) in diameter over a period of 14 months resulted in an arrester blockage equivalent to 35 percent reduction of the arrester area.

Staff (Forest Products Laboratory U. S. Forest Service, Madison, Wisconsin) "Exploratory Investigation of Fire-Retardant Treatments for Particleboard," *U.S.D.A. Forest Service Research Note FPL-0201* (August 1969)

Section: A
Subjects: Fire retardants; Particleboard

Staff Abstract

More than 80 exploratory experiments were made on the development of fire-retardant-treated particleboard using 15 fire retardant chemicals, 3 resin binders,

2 species of wood, and various types of application. Among the types of application were those employing solutions of fire retardant salts sprayed on green flakes; and others employing dry, finely divided fire retardants added after mixing binder resin and flakes. Of the boards produced and tested, several using certain borates, AWPA Type C and Type D fire retardants, and monoammonium phosphate showed promise. Properties considered were flame spread, smoke production, strength, and stability. Salts applied in solution to green wood, followed by drying, gave results superior to those obtained from the use of dry fire-retardant salts. None of the boards were tested for fire retardance and strength after cycling through changing humidities. The results of this series of experiments are released in the form of a progress report for use by others engaged in similar studies.

B. Ignition of Fires

Averson, A. E. and Rozenband, V. I., "Approximate Methods of Calculating the Critical Ignition Conditions," *Physics of Combustion and Explosion* 4, 455–468 (1968) In Russian.

Sections: B, H, G
Subjects: Critical ignition; Thermal theory

Authors' Summary—Translated by L. J. Holtschlag

A brief analysis is made of the critical phenomena taking place at ignition from the viewpoint of a thermal theory based on the leading part played by reactions in the condensed phase. Approximate methods permitting calculation of the conditions responsible for these phenomena are discussed. Two cases are examined, namely, ignition is initiated by heat from pulsed and continuous external sources. An example is ignition by a plate of finite thickness, where the surface temperature and the heat flux decreases slowly enough to allow a heated layer to form in the material, resulting in a self-accelerating chemical reaction. The scheme can be used to predict critical ignition phenomena in the case of time-variable heat-transfer conditions. The method of calculating critical ignition conditions based on comparison of the rates of external heat supply and heat release by chemical reaction can be used to solve a number of problems of the thermal theory of ignition.

Bracciaventi, J. (Naval Applied Science Laboratory, Brooklyn, New York) "Fire Start Capabilities of Nuclear Detonations in Urban Areas," *Final Report under Office of Civil Defense Contract OCD-DAHC-20-70-C-0230* (September 1969)

Sections: B, M
Subjects: Fire starts; Ignition; Nuclear weapons; Urban fires

Author's Abstract and Summary

A method for predicting the distribution of primary ignitions in urban areas due to nuclear detonations is presented. The model calculates separately the number of expected ignitions in window fuel arrays, tinder fuel arrays interior to rooms, and exterior fuel arrays. Fuel distributions and distributions of urban characteristics are utilized in the calculation. Shadowing by buildings and obstructions, and attenuation by window panes, and screens are considered. Fire-start capabilities of the ignitions are described by enumerating the ignitions by zones in each occupancy or use-class together with estimates of their burning times and fuel values. The fuel load in each zone due to major fuels and kindling fuels is also specified.

The most important parameters considered are:

a. orientation of target elements with respect to the burst
b. free field radiant exposures
c. density of each use-class in the area
d. shadowing by obstructions
e. distribution of windows
f. distribution of attenuators
g. distributions of blinds and shades
h. volumes of rooms exposed
i. areas of site-exteriors exposed
j. distributions of window fuel arrays, interior fuel arrays, and exterior fuel arrays

The model calculates separately the expected ignitions in window fuel arrays interior fuel arrays, and exterior fuel arrays. Fire-start capabilities of the ignitions are expressed by giving their burning times and fuel values, and the fuel load of the zone in which the ignitions occur.

Gregor'ev, Iu. M., Gontkovskaia, V. T., Khaikin, B. T., and Merzhanov, A. G., "Theory of Evaporation and Ignition of a Droplet of Explosive," *Physics of Combustion and Explosion* **4**, 526–539 (1968). In Russian.

Section: B
Subjects: Droplets; Evaporation; Explosives; Ignition; Induction period

Authors' Summary—Translated by L. Holtschlag

A theoretical and experimental study is made of the evaporation and ignition of a droplet of volatile explosive in an infinite inert gas medium. The ignition method

used in the analysis is based on the concept of the limiting role played by the exothermic reaction in vapors in the absence of heat sources in the condensed phase. The equations describing droplet evaporation and ignition are derived from the transfer equations in a two-component system. The theoretical models were investigated experimentally with methyl nitrate in air and nitrogen in the temperature range of 20° to 300°C. The ignition limits are found to be essentially identical. The activation energy was $E+36{,}000$ cal/mole, which is close to the heat of $O–NO_2$ bond rupture. The data obtained from determination of the time characteristics of evaporation and explosion and also the magnitude of the change in droplet size during the induction period are compared with quantitative results of the theory and are displayed in graph form.

Lisitskii, V. I. and Pribytkova, K. V., "Ignition of Condensed Materials in the Presence of a Phase Transition in the Heated Layer," *Physics of Combustion and Explosion* **4,** 501–512 (1968). In Russian.

Section: B
Subjects: Condensed materials; Ignition; Phase transition

Authors' Summary—Translated by L. Holtschlag

Approximate solutions are derived for the problem of ignition in the presence of phase transition in the heated layer of a semi-infinite homogeneous material. The temperature of the material at the start of the process is lower than that of the phase transformation, so that heat is exchanged with the ambient medium by Newton's law. The accuracy of the solutions is estimated by comparison with a computer calculation. The effect of various phase-transformation parameters on the ignition characteristics is analyzed. An example is given of calculation of the ignition delay time for ammonium perchlorate, taking into account the polymorphic phase transition. The results show that the effect of the phase transition of ammonium perchlorate under these conditions is insignificant, and the usual relations of the thermal theory can be used for calculation of the basic ignition properties.

Nakauchi, S. (Fire Research Institute of Japan, Tokyo, Japan) "On the Ignition of Wood by Leakage Current of Electricity I," *Report of Fire Research Institute of Japan* **4** (4), 85 (December 1953)

Sections: B, I
Subjects: Electrical leakages; Ignition; Wood

Author's Abstract

Ignition phenomena of wood, when a leakage current of electricity passed through it, were investigated. The possibility of kindling wood by leakage current depends on the species of wood, the degree of dryness and the thickness of the sample, the size of the electrodes, the voltage applied, the current density, the time the current passed, and the influence of water film produced on the wooden surface are discussed.

The samples of wood used in the experiments were cedar plates 7 mm in thickness, dried in the atmosphere. Electrodes of 2 mm in diameter each were driven into the sample and it was dipped in water and a water film was formed on its surface just before the experiment, and then, the current was sent. As the greater part of the current passed through the film of water and the Joule's heat evaporated it, dry areas appeared in the neighbourhoods of the electrodes and increased their boundaries gradually. In this stage, as nearly all the applied voltage dropped on the dried spans, if the voltage of the source was higher than a certain value, failure of insulation took place in these parts and small sparks appeared in the wooden body, leaving charred marks in it. Figures 2 and 3 show such charred patterns.

Figure 4 is an example of records of leakage currents in the case of open voltage 9000 short-circuited current 10 mA., and electrode distance 10 mm.

The results of my experiments showed that the possibility of kindling wood by leakage current depends not only on the current density, but greatly on the voltage applied. When the voltage of the source was 9000, a current of 8 mA could ignite wood, while it was impossible to kindle wood by any current through it when the voltage was 100.

When the distance of the electrodes was 10 mm the voltage more than 400 was necessary to send steady current through wood for one hour, after charred track was produced between poles. When the voltage of the source was 300, the current diminished rapidly and tended to zero after a few minutes.

A charred layer on a surface of wood produced by leakage currents does not show the characteristics of ordinary resistances, but it has a character the same as a resistance and a constant voltage discharge tube in series. An account of such an equivalent circuit will be described in the second report.

Nii, R. (Fire Research Institute of Japan, Tokyo, Japan) "Ignition of Combustible Liquids by Heat Sources of Solids of Small Size I and II," *Report of Fire Research Institute of Japan* 5 (2), 19 (1955) and 6 (2), 14 (1955)

Section: B
Subjects: Cigarets; Heat sources; Ignition; Liquids; Solids

Author's English Summary

I. Some investigations of ignition of mixtures of oxygen or air and hydrogen, natural gas, and methane by heated metals were done previously. But there are few investigations of ignition by heat sources of solids of mixtures of air or oxygen and vapors of combustible liquids as carbon disulphide, benzene, gasoline etc., which are classified as dangerous materials in the Fire Service Law in Japan.

It is often reported that ignitions and explosions of combustible mixtures as mentioned above were caused by heat sources of solids of small sizes, for example, a heated spatula or a kindling piece of cigaret, etc.

As it is yet vague whether the combustible mixtures are ignited or not by such a heat source of solid as mentioned above, the experiment was carried out in order to make clear what is vague with respect to the ignition of the combustible mixtures by heat sources of solids of small sizes. In the experiment, wires of small sizes consisting of a few kinds of metals and of different diameters, heated by electric current as heat sources of solids, were used.

The results of the experiment in the 1st Report can be summarized as follows:

(1) The ignition temperature determined from the author's experiment was of considerably higher temperature compared with that done previously by the other methods of measurement of ignition temperature—i.e., 1100°–1200°C for all combustible mixtures used, but for carbon disulphide below, 700°C.

(2) No difference was found in the ignition temperature of the combustible mixture when various kinds of metals were used as heated wires.

(3) As the error of measurement of the surface temperature of the heated wire was about a maximum of ±50°C, the difference of ignition temperature due to that of the mechanism.

II. The author already reported in the first report about the results of experiment on the ignition of combustible liquids by heated wires of small sizes. Thenceforth the experiment was carried out continuously in order to answer to a few questions: whether it is ignited by dropping a burning cigaret into a mixture of vapor of such a combustible liquid as carbon disulphide, or gasoline, or ether, and so on, and air, or not; if ignited, how many frequencies of ignition about a concentration of the combustible mixture there are; and at what range of concentrations of the mixture it is ignited.

The results of experiment in this report give us a few answers as follows:

1. There is no possibility of ignition by a burning cigaret on combustible liquids of Self-Ignition Temperature (S.I.T. greater than 220°C. Benzene, acetone, 65–87 octane gasoline (B.P. = 50°–100°C)are examples.

2. A burning cigaret can ignite ether and carbon disulphide. There is a special danger with carbon disulphide being ignited and exploded.

3. The most dangerous case occurs when a lump of burning cigaret separates from the nonburning part of the cigaret and drops into such a combustible mixture of less than 180° at S.I.T., such as ether or carbon disulphide.

Rozenband, V. I., Averson, A. E., Barzykin, V. V., and Merzhanov, A. G., "Certain Laws Governing Dynamic Ignition Regimes," *Physics of Combustion and Explosion* 4, 494–500 (1968). In Russian.

Section: B
Subjects: Condensed phase; Ignition; Ignition delay; Regimes

Authors' Summary—Translated by L. Holtschlag

On the basis of the thermal theory of ignition, in which it is assumed that the principal processes leading to ignition take place in the condensed phase, some laws governing dynamic ignition regimes are examined. The effect of the form of the external heat on determination of the ignition delay and its dependence on the kinetic and thermophysical parameters of the material, as well as the accuracy of determination of the kinetic parameters on the basis of ignition experiments, are investigated. Use of the integral method to solve a nonlinear heat-conduction equation shows that the effect of the chemical reaction on the temperature growth is governed by the ratio of the heat released in the material to the external heat supplied, the effect varying as a function of the time dependence of the external heat flux. The accuracy of determination of the kinetic parameter also depends on the heat-transfer conditions, the optimal situation prevailing when the external heat flux decreases with time.

Tolstykh, N. D. and Pavlysh, B. P., "Ignition Mechanism of the Electric Igniter of Industrial Electric Detonators," *Physics of Combustion and Explosion* **4,** 607–610 (1968). In Russian.

Section: B
Subjects: Detonation; Igniter; Ignition mechanism; Induction period

Authors' Summary—Translated by L. Holtschlag

To ensure the reliability of group detonation of series-connected electric detonators, it is necessary to determine the transfer time experimentally in order to develop a method of controlling it. This is done by oscillographic observation of the fuzing mechanism of an electric igniter. From the results a detailed description is given of the fuzing mechanism (in three steps: heat-up of the heating bridge and igniter compound; induction period; ignition of compound). It is concluded that for reliable group detonation of electric detonators, it is necessary that the time scatter of the igniting pulses be less than the minimum induction time.

Viliunov, V. N., "Critical Condition of Ignition of Gas Mixtures by a Hot Center and Laws Governing Steady-State Flame Propagation," *Physics of Combustion and Explosion* 4, 513–518 (1968). In Russian.

Section: B
Subjects: Critical ignition; Flame propagation; Gas mixtures; Hot center

Author's Summary—Translated by L. Holtschlag

A theoretical analysis is made of steady-state flame propagation in a gas mixture; also given are the limits of extinction and ignition. The cases of spherically symmetric, cylindrical and plane propagation are examined. The process of establishment of the steady flame propagation condition is described by a system of nonlinear parabolic equations, one being the heat-conduction equation, the others the equations of diffusion of the initial, intermediate, and final reaction products in the flame zone. The rate of flame front propagation was determined by tracing the rate of advance of fixed points of the dimensionless temperature profile. The results showed that the Lewis and von Elbes idea of "excess enthalpy" in the problem of ignition by a hot volume is inadequate, since it was found that the critical flame size also exists when the enthalpy is deficient, and therefore the "excess enthalpy theory" is in need of reexamination.

Waterman, T. E. and Takata, A. N. (IIT Research Institute, Chicago, Illinois) "Laboratory Study of Ignition of Host Materials by Firebrands," *Final Technical Report under Office of Civil Defense Contract No. 0228-68-C-2367* (June 1969)

Section: B
Subjects: Firebrand; Host materials; Ignition; Urban fire

Authors' Summary

The mode of urban fire spread most lacking in quantitative definition is that of the propagation of fire by flying brands. Unlike the forest fire where useful statistical data can be collected, the urban fire is usually fought with sufficient resources to effectively counteract brand production, even though significant local damage is wrought. Those occasional wartime exceptions to this rule do not lend themselves to detailed analysis since the inherent mass confusion that accompanied those holocausts prohibited all but very delayed "postmortem" attempts to classify the role played by brands.

In order to derive needed information on firebrand contribution to fire spread, the Office of Civil Defense has initiated laboratory and field studies into the several stages of firebrand life. The present study is directed at examining, on a laboratory scale, the susceptibility of interior and exterior host materials to various brand ignitions. Some of the more significant conclusions that were obtained are listed below:

—The larger brands (greater than 1 sq. in.) formed from sheathing lumber constitute the most hazardous brands due to their inherent ability for self-reinforced glowing combustion.
—Wood shingles form brands that are poor igniters. However, weathered wood-shingle roofs are extremely susceptible to brand ignitions.
—Exterior hosts of sound wood, although frequently found, are not susceptible to brand ignition and most brands can be considered to be merely the sparks for pilot ignitions where radiant-heating levels are sufficiently great.
—The majority of susceptible urban hosts are interior materials.
—The most readily ignited interior hosts are beds and upholstered furnishings where cotton batting is used as padding.
—Blast damage increases ignition probability from brands by removing windows and roofs and thus increasing probability of impingement. Blast-damaged structural lumber and overturned furnishings show no marked increase in susceptibility to sustained brand ignition.

—In a nuclear emergency in which windows are blown out, firebrands will generally be a major source of fire spread.
—The brand threat would be maximum in densely built-up areas containing tall buildings of non-fire-resistive construction and with appreciable window openings and interior fuels.

Waterman, T. E. (IIT Research Institute, Chicago, Illinois) "Experimental Study of Firebrand Generation," *Final Report under Office of Civil Defense Contract No. 0228-67-C-2774* (January 1969)

Sections: B, D
Subjects: Fire spreads; Firebrands

Author's Abstract

Experiments were performed to assess the capability of various roof constructions to produce firebrands when subjected to a building fire. These tests of roof segments were conducted by placing the roofs over the top of a two-story fire chamber and, by means of a screen trap and quenching pool, collecting all brands generated. Effects of different building heights (unrestricted fire height) and wind-induced internal pressures were simulated by imposing additional pressure on the fire chamber interior.

Results indicate that changes in internal pressures produced marked changes in brand production. Of the roof constructions evaluated, wood shingled roofs were by far the greatest brand producers. Over the range of roofs and imposed conditions studied, the brands produced were of low density and appeared to be in a state of glowing combustion at the time of their generation, or shortly thereafter.

C. Detection of Fires

Lawson, D. I. (Joint Fire Research Organization, Borehamwood, England) "Memo on Potential Saving That Might Be Effected by Rapid Fire Detector," *Joint Fire Research Organization Fire Research Note No. 781* (September 1969)

Section: C
Subjects: Cost effectiveness; Fire detection; Rapid detection; Savings

Author's Summary

From the records of over a thousand large fires the number which became large through delay in discovery is known. From these the proportion which would have probably become large through faulty building design, etc., has been discounted and it has been assumed that the rest could have been prevented from becoming large by the provision of an automatic detection system.

Nakauchi, S. and Tsutsui, Y. (Fire Research Institute of Japan, Tokyo, Japan) "A Study on the Pneumatic Tube-Type Fire Detector," *Report of Fire Research Institute of Japan* 7, No. 1, 2, 1–60 (December 1956)

Section: C
Subjects: Detector; Fire detector; Pneumatic tube.

Authors' English Summary

In view of the recent increasing use of the pneumatic-tube-type fire detector in Japan, a study has been made of its operating characteristics to derive criteria for optimum design and establish a practical method for testing the products.

This report begins the descriptions of the work with some introductory remarks in Chapter 1, where a schematic diagram (Fig. 1.1) is inserted to give an idea of the construction of the detector to be dealt with. In this diagram: (1) is a pneumatic tubing that can be fitted around ceilings of a few rooms in continuous loops. The tubing is made of copper and has an inside diameter of 0.14–0.20 cm and a total length of 200 m. (2) is a pressure-sensitive apparatus, a corrugated diaphragm provided with electrical contacts. (3) are electrical contacts which close when the diaphragm is increased due to a temperature rise at the tubing. (4) is an air-leak vent for discriminating a rapid temperature rise from a slow one.

In Chapter 2 are the mathematical analyses of the behavior of the detector in terms of the temperature rise produced at any portion of the pneumatic tubing. Theoretical formulae have been deduced here for calculating the pressure rise in the diaphragm for cases where the temperature of the tubing is raised (i) abruptly, (ii) linearly, and (iii) exponentially with time. The calculations by these formulae are comparatively simple and the theory is later used in Chapter 4 where the problems of optimum design and testing method are considered. References are also made here to experimental observations carried out to confirm the theory, indicating that a good agreement between the measured and calculated values has been obtained.

In Chapter 3 are described the theoretical and experimental investigations of the manner in which the temperature of the pneumatic tubing varies at the incipient stage of actual fire or room heating. Characteristic temperature rises determined for these two cases are proposed here.

Chapter 4 is devoted to a guidance for designing a reliable and inexpensive detector. Theoretical procedures for deciding the dimensions of the pneumatic tubing and optimum diameter and stiffness of the diaphragm are presented here. Also given here are the procedures to determine the amount of leakage through the air-leak vent and the gap between the electrical contacts, provided the diameter of the penumatic tube and the characteristics of the diaphragm have been predetermined. The proposed theory for design is believed to be always applicable, should there be any revision of the specifications for the detector owing to the possible progress in the method of room heating or changes in the architectural style.

Further, on the basis of the above-mentioned theoretical treatments for design, the authors have introduced a practical method for testing the products. Until the work was undertaken, the only way to check the performance of the detector had been to heat the pneumatic tubing actually by hot air. This method takes a great deal of time if exact results are required. In the proposed method, the inspector need only measure the leakage at the leak vent, the gap between the electrical con-

tacts, and the diameter as well as the total length of the pneumatic tubing. By applying the authors' theoretical formulae to these measured values, the overall characteristics of a detector can well be clarified. The proposed method has an advantage over the heating-the-pneumatic-tube method in that the whole procedure can be performed in only a few minutes and yet more reliable results are assured.

Putnam, T. M. and Parker, J. R. (Los Alamos Scientific Laboratory, Los Alamos, New Mexico) "Tests of Combustion Product Detectors in a Radiation Environment," *Fire Technology* 5, 273–283 (1969)

Section: C, N
Subjects: Combustion; Combustion products; Detectors; Radiation environment

Authors' Conclusions

The results of the tests of ionization-type combustion product detectors in a high level radiation environment were conclusive. This type of detector will not work in the environment of the LAMPF beam channel when the accelerator is in operation. Further, due to the generation of ozone by the radiation flux, ionization-type detectors are apt to go into alarm immediately following beam turnoff.

It should be noted that the program was not designed to test the relative response times of the various detectors for which this time was of approximately the same magnitude. The combustion product densities were not uniform enough for comparison. Therefore, no conclusion should be drawn from the test data regarding the no-beam response of the various detectors.

O'Dogerty, M. J., Young, R. A., and Lange, A. (Joint Fire Research Organization, Borehamwood, England) "Experiments on Smoke Detection . Part 2. Fires in Wood Cribs, Rubber Cribs, Polyvinyl Chloride Powder and Petrol," *Joint Fire Research Organization Fire Research Note No. 780* (September 1969)

Section: C
Subjects: Fire; Flammable liquid; Petrol; Polyvinyl chloride; Powders; Rubber; Smoke detector; Solids; Wood

Authors' Summary

Experiments are described on the measurement and detection of smoke in a room 2.46 m (8 ft 1 in.) high, having a volume of 153 m^3 (5400 ft^3). The fires were in wood cribs, rubber cribs, petrol and polyvinyl chloride powder, which were sited at a range of horizontal distances up to 6.10 m (20 ft) from the measuring and detecting equipment. Measurements were made of the optical density of the smoke, the rise in air temperature, and the response times of two types of proprietary smoke detectors.

E. Suppression of Fires

Gordon, J. A. and Prince, H. C. (Joint Fire Research Organization, Borehamwood, England) "Investigation into the Processes Governing the Operation and Discharge of Fire Extinguishers," *Joint Fire Research Organization Fire Research Note No. 767* (May 1969)

Sections: E, N, I
Subjects: Discharge; Extinguisher (hand operated); Fire extinguisher

Authors' Summary

To make an assessment of the design, performance, and safety in use of fire extinguishers which are submitted for approval, it was necessary to obtain a picture of the processes governing the operation and discharge of extinguishers of various types.

Nii, R. (Fire Research Institute of Japan, Tokyo, Japan) "Drainage of Air Foam in Case of Coexistence with a Principal Ingredient of Dry Chemical Extinguishing Agents and with a Petroleum," *Report of Fire Research Institute of Japan No. 23* (1963)

Sections: E, F
Subjects: Coexistence; Drainage; Dry chemical; Extinguisher; Foam; Petroleum

Author's English Summary

Air foam and dry chemical extinguishing agents are used at the same time in some recent cases of aircraft fires. We cannot use in these cases an ordinary type of dry chemical powder for B-fire (the classification of fire in Japan), because the dry chemical powder, which consists of $NaHCO_3$ as a principal ingredient and a metal stearate as an additional, breaks up air foam faster.

Some new types of dry chemicals, which are compatible with air foam, have been lately brought to market in the U.S.A. and West-Germany. However, it is not clear how much air foam is influenced by such chemical reagents as $NaHCO_3$, or $KHCO_3$, or $CaCO_3$, or $(NH_4)_2HPO_4$, which is available for the dry chemical extinguisher on an extinguishing principle, when it is mixed up homogeneously with a chemical reagent as mentioned above.

An experiment about drainage of an air foam of protein base (Schaumgeist 36) was made by the author in the case of additions of those chemical reagents as mentioned above, and some petroleums differed in boiling point. (See Fig. 1 for the experimental apparatus.)

The author is led to some conclusions from the result of the experiment as follows, as far as it concerned the 25% drainage time of the air foam used (See Figs. 2, 3,

4, 5 for details):

1. In case of some addition of $NaHCO_3$, or $CaCO_3$, or $(NH_4)_2HPO_4$, but no addition of petroleum to the air foam solution, no decrease of the 25% drainage time is found except in the case where the added amount of $(NH_4)_2HPO_4$ is 2 g in weight. The addition 2 g in weight gives only a little decrease on the 25% drainage time. Some addition of those chemical reagents, therefore, does not desirably influence the air foam.

That a useful dry chemical extinguishing agent only for B-fires is not compatible with air foam is due not to $NaHCO_3$ but to metal stearate.

2. In case of both additions, $NaHCO_3$, or $KHCO_3$, or $CaCO_3$, or $(NH_4)_2HPO_4$ and a petroleum to the air foam solution, the author can point out the following:

(a) The 25% drainage time in the case of some addition of a petroleum, which is less than 60°C at boiling point, is much larger than that of no addition of petroleum.

(b) In the case of both additions of another petroleum, which is from 100° to 150°C or 150° to 180°C at boiling point, and $NaHCO_3$ or $CaCO_3$, the 25% drainage time shows some decreases; in the other case of both additions of the same petroleum and $KHCO_3$ or $(NH_4)_2HPO_4$, the 25% drainage time shows some increases, in comparison with that of no addition of petroleum.

The chemical reagents $CaCO_3$ and $(NH_4)_2HPO_4$ have a hopeful possibility of application as dry chemical powders compatible with air foam. This experiment was carried out in 1961 at d. Forschungsstelle für Brandschutztechnik at d. T. H. Karlsruhe, West-Germany. The author wishes to express sincere thanks for the kind instructions and help of the director of the Forschungsstelle, Dr. G. Magnus, Dr. M. Friedrich and his coworkers.

Geffs, T. (Parker Hannifin Corporation, Cleveland, Ohio) "Fuel Tank Inerting and Fire Fighting with Liquid Nitrogen," *Fire Technology* **5,** 193–196 (1969) and **Klueg, E. P.** (National Aviation Facilities Experimental Center, Atlantic City, New Jersey) "Liquid Nitrogen as a Powerplant Fire Extinguishant," *Fire Technology* **5,** 197–202 (1969)

Section: E
Subjects: Fuel tank; Fire fighting; Inerting; Liquid nitrogen

Reviewed by G. A. Agoston

A fuel tank inerting system (Parker Hannifin) employing liquid nitrogen to protect aircraft from the hazard of fuel tank explosion is now being flight-tested aboard military aircraft. The presence of ample quantities of liquid nitrogen aboard may justify its use for protecting the powerplants as well. The first paper is a discussion of the two applications; the second is a preliminary report on the suitability of liquid nitrogen for fire extinguishing.

The system provides protection by maintaining an oxygen concentration in the vapor space of the fuel tanks that is too lean to support the propagation of flame. Oxygen dissolved in the fuel is released during depressurization in climbing. In this system nitrogen gas is bubbled through the fuel to "scrub" the oxygen out and to dilute it to a safe concentration; the oxygen containing mixture is then vented overboard. (Water in the fuel is removed simultaneously.) A second source of oxygen (and moisture) is the air sucked into the tanks when the fuel is being removed. The Parker system prevents this by means of valves in the vent line that permit the exit flow of gas but not the inward flow, owing to a positive nitrogen pressure in the tanks of 0.25 to 9.5 psi.

The system is lightweight, inexpensive to operate and fully automatic. An ample liquid nitrogen supply also makes feasible its use as a refrigerant in maintaining liquid oxygen held for emergency breathing. The use of liquid oxygen eliminates the explosion hazard created by high pressure gas.

On the weight basis liquid nitrogen is superior to carbon dioxide in fire extinguishing because of its greater cooling and greater oxygen dilution. Although it does not surpass the halogenated agents (e.g., $CBrF_3$ and CBr_2F_2), which have the additional property of interfering with combustion reactions, it is practical as an extinguishant when large quantities are available.

The second paper is a summary of certain preliminary tests in an investigation conducted by the Federal Aviation Administration. The tests are being made on an instrumented JT-12 turobjet engine and nacelle mounted in a wind tunnel that simulates subsonic, low altitude flight conditions. A liquid nitrogen discharge system having four fog nozzles was developed for the powerplant. In the tests to date local fires were started in a spark ignited JP-4 jet fuel spray (flowing at 0.1 gpm) in an area remote from the fog nozzles.

In each test the JT-12 engine was retarded to cutoff 5 sec after starting the test fire. The nitrogen discharge (rates of 0.2 to 3.2 lb/sec) was always initiated 10 sec after retarding the engine and continued for periods of 3 to 16 sec.

The effectiveness of liquid nitrogen appeared to be primarily a function of the rate at which it was discharged. At an air flow of 0.5 lb/sec, the discharge rate was 0.6 lb/sec; at an air flow of 3.0 lb/sec, it was 1.1 lb/sec. Extinguishment occurred generally within 2 to 3 sec after initiating the liquid nitrogen discharge. Additional cooling to decrease the possibility of reignition may be achieved by the further release of nitrogen: liquid nitrogen at 1 lb/sec for 7 sec reduced the temperature about 100° or 150°F. It is estimated that, on the basis of weight, about 3 or 4 times more liquid nitrogen as compared to bromotrifluoromethane is required for extinguishment.

Study of these preliminary data suggests that a dilution of oxygen to approximately 10 percent (completely mixed system) was required at low air flow; while at high air flow fires were extinguished at oxygen concentrations somewhat above 15 percent. Since at high air rates the test fires were probably burning lean, higher fuel release rates would demand increased nitrogen discharge rates resulting in lower oxygen concentrations.

Consideration is being given to additional questions such as the line length and diameter, the discharge nozzle, cooling and oxygen dilution, storage pressure, thermal shock to engine components and evaluation of powerplant installations utilizing liquid nitrogen for fire extinguishing.

Thorne, P. F., Tucker, D. M., and Rasbash, D. J. (Joint Fire Research Organization, Borehamwood, England) "Notes on the Use of High Expansion Air Foam in Fire Fighting," *Joint Fire Research Organization Fire Research Note No. 766* (May 1969)

Section: E
Subjects: Extinguishment; Foam; High-expansion foam

Authors' Summary

This note is intended as a guide on the use of High Expansion Air Foam (H.E.A.F.) for fire fighting. It contains recommendations on the generation and deployment of foam and suggests minimum application rates for various fire risks.

F. Fire Damage and Salvage

Ames, S. A. (Joint Fire Research Organization, Borehamwood, England) "The Effect of a Commercial Aerosol on the Rate of Recovery of Wetted Electric Motors," *Joint Fire Research Organization Fire Research Note No. 778* (August 1969)

Section: F
Subjects: Aerosol; Electric motors; Electrical equipment; Recovery; Sprays; Water

Author's Summary

An investigation was carried out into the improvement of the insulation recovery rate of wetted electric motors by use of a commercially prepared aerosol. No marked difference in recovery rate was observed between treated and untreated motors.

Martin, S. B. and Ramstad, R. W. (URS Research Company, Burlingame, California) "Capabilities of Fire Services to Limit Damage from Nuclear Attack," *Final Report under Office of Civil Defense Contract NO028-696-5* (May 1969)

Sections: F, L
Subjects: Capabilities; Damage Control; Fire Services; Nuclear attack

Authors' Abstract

The objective of the reported research was to develop a general analytical method for evaluating the potential effectiveness of fire services under nuclear attack conditions and to determine a set of modes of fire-service operation which would make the best use of the fire services.

This study is a continuation of earlier research conducted under OCD Work Units 2512A and 2522E. Its approach is to extend the concepts and analytical methods developed in the earlier studies and to apply them in the analysis of: (1) the feasibility of various fire-service tactics and activities, and (2) the levels of performance and relative effectiveness of fire-service operations when various concepts of preattack deployment, augmentation (with nonprofessional manpower), strategies, and tactics are employed in meeting transattack demands.

The quantitative evaluation of fire-service effectiveness requires analytical expressions describing the performance of each of the candidate damage-control tasks. Some of these were derived in the earlier studies. The development of additional relationships was accomplished during the investigation reported here.

G. Combustion Engineering

Abramov, V. G. and Merzhanov, A. G., "Thermal Explosion in Homogeneous Flow Reactors," *Physics of Combustion and Explosion* **4,** 548–556 (1968). In Russian.

Section: G
Subjects: Homogeneous reactors; Induction period; Thermal explosion

Authors' Summary—Translated by L. Holtschlag

An analysis is made of the operating modes of several types of homogeneous flow reactors from the standpoint of the theory of thermal explosion. The critical conditions and induction periods of thermal explosion are determined for various reactors (ideal mixing, ideal displacement and ideal displacement with longitudinal transfer). Estimates are given for the critical condition and induction periods of the thermal explosion of hydroperoxide of isopropylbenzene, the intermediate product in the production of phenol and acetone, in the still of a fractionating column.

Akita, K. and Aonuma, T. (Fire Research Institute of Japan, Tokyo, Japan) "Some Calculation for the Investigation and Prevention of Fire due to Fireworks," *Report of Fire Research Institute of Japan* (July 13, 1955)

Sections: G, N
Subjects: Fireworks

Authors' English Summary

In summer, fireworks exhibitions are often held in Japan and fires caused by fireworks are not rare. To investigate the prevention of such fires, a calculation of the falling rate and displacement of fireworks by wind is given in this Report.

Fireworks with parachutes can be carried by wind over a great distance. There is a possibility that parts of fireworks reach the ground still burning.

Artiukh, L. Iu., Vulis, L. A., Luk'ranov, A. T., and Sharaia, S. N., "Numerical Solution of the Problem of Nonstationary Heating of a Fuel Mixture in a Vessel," *Physics of Combustion and Explosion* 4, 557–562 (1968). In Russian.

Sections: G, H, I, B
Subjects: Fuel-air; Heating; nonstationary; Thermal explosion

Authors' Summary—Translated by L. Holtschlag

Some results are given of the numerical solution to the classical problem of thermal explosion of a combustible mixture in a vertical, infinitely long cylindrical vessel. The possibility of solving the nonlinear equations of heat conduction with an Arrhenius source by computor simulation is studied. A comparison is made of the results of numerical analysis by various explicit and implicit finite-difference schemes. The main purpose was to study the response of the system under finite perturbations produced by varying the boundary conditions, especially by instantaneous or prolonged increase in temperature at the wall of the vessel, yielding additional information on the nonstationary thermal regime of a nonlinear system, e.g., the point of thermal explosion shifts continuously toward the wall as the amplitude of the instantaneous temperature perturbation is increased.

Becker, H. and Brown, A. (Queens University, Kingston, Ontario, Canada) "Velocity Fluctuations in Turbulent Jets and Flames," *Twelfth Symposium* (*International*) *on Combustion*, Pittsburgh, The Combustion Institute, 1059 (1969)

Sections: G, I
Subjects: Flames; Turbulent jets; Velocity fluctuations

Reviewed by F. Falk

The authors present two pressure measuring devices for characterizing, quantitatively, turbulence in flames. One of these is a "differential Pitot," the functioning of which is based on the difference in response of two Pitot tubes with differently shaped heads. The other is a flat-plate static pressure probe which utilizes the static pressure defect that is directly related to the radial velocity fluctuations in symmetrical turbulent shear flow.

Measurements were made in jets with nozzle momentum flux of 0.475 kgm/sec^2. With air/air and nonburning propane/air this gave a nozzle Reynolds number of 45,000; with combustion in a propane/air jet the local Reynolds number decreased due to the temperature rise by as much as a factor of 10.

The static probe had a highly polished flat face with razor-sharp edges. Two probes were tested; one with a 0.6 cm diameter, the other with a 1.3 cm diameter, both with a 0.046 cm hole. With these probes it was expected to determine the normal radial Reynolds stress $\langle \rho u_r^2 \rangle$ from the static pressure defect. Centerline data are presented which show little difference in the amplitude of the defect between the air/air and the flame jets. A comparison between the present results and previous results obtained with hot-wire anemometers[1,2] shows very good agreement.

Relative to the "differential Pitot" it is shown that the difference between the total pressure sensed and the static pressure at the shear flow edge is related to the impact coefficient, the yaw angle, and a turbulent scale factor. The impact coefficient varies with the shape of the probe nose. Thus, when a thin-walled, squarely-truncated, hollow cylindrical probe is coupled against a sphere-nosed probe with a very small top, the response should be $\Delta q = \frac{1}{2} A \bar{\rho} \langle u_r^2 + u_\phi^2 \rangle$. For the measurements presented in this paper, the cylindrical probe had an O.D. = 1.29 mm and an I.D. = 0.83 mm while the spherical probe had a nose diameter of 4.75 mm and a top of 0.40 mm. diameter.

The response of the differential probe was quite linear up to a yaw angle of 10° and reasonably linear to 25°. Data taken with this system showed more scatter than that obtained with the flat-face static probe. There is evidence that the sphere was too large relative to the turbulence intensity.

It appears that the static probe can be used to indicate the radial velocity fluctuations reasonably well whereas the differential probe requires additional work before its adequacy is demonstrated.

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Guenther, R. and Simon, H. (University of Karlsruhe, Karlsruhe, Germany) "Turbulence Intensity, Spectral Density Functions, and Eulerian Scales of Emission in Turbulent Diffusion Flames," *Twelfth Symposium (International) on Combustion*, Pittsburgh, The Combustion Institute, 1069 (1969)

Sections: G, I
Subjects: Emissivy; Eulerian scale; Diffusion flames; Turbulent intensity

Reviewed by F. Falk

This report presents a procedure and describes an apparatus for the quantitative measurement of fluctuations of flame emissions which can be used for the observation of a small region of a flame.

To measure the fluctuations, an optical probe was designed which observed a 5-mm-thick portion of the flame while disturbing the flow field in the area of the measurement as little as possible. Information on eddy size was inferred from the concentration of active particles in the reaction field of the turbulent flame assuming the reaction to occur in the borders of the eddies. Using a photomultiplier and a blocking-layer photocell as receivers, a range of 300 to 1200 mm could be covered up to a frequency of 12 kHz without distortion.

It was assumed that the reaction zone consisted of a broad spectrum of sizes of eddies and that these eddies remain unchanged during the period of observation, i.e., approximately 10^2 to 10^4 seconds. Emission by radicals C_2, CH, OH, and HCO characterizes the eddies since these short-lived species exist mainly in the reaction zone. To minimize the effect of emission from soot, CO_2 and H_2, the fuel, jet momentum, and wavelength to be measured were carefully selected. Measurements at a distance of 120 diameters indicated that those longer-lived species did not influence the emissions.

The authors compare their results of the degree of turbulence on the axis of the flame and at two cross sections with those obtained by two other methods which have been used in their Institute.[1,2] All methods show considerably lower degree of turbulence in a turbulent diffusion flame than is found in an isothermal jet. The other two methods, dependent on velocity fluctuations, show a strong similarity to each other. Where reaction can be expected to be well past its initiation stage, agreement between the emission-dependent and velocity fluctuation-dependent techniques is satisfactory. Where reaction is not well advanced, the emission technique shows a much lower degree of turbulence.

The degree of turbulence determined by the emission technique for a number of cross sections from 20 to 70 diameters is presented and show two maxima. These are thought to represent the extremities of the main reaction field. This is in accordance with the disappearance of the inner maximum by 70 diameters, by which time a stoichiometric composition has been reached on the axis.

From a normalized spectral density function, based on Taylor's[3] application of harmonic analysis to turbulent fluctuation and an exponential law for the correlation from Dryden,[4] it is shown that the combustion process has no influence on the detailed spectral ranges. The reaction causes no selective changes of discrete portions of the spectrum.

A plot showing lines of equal Eulerian scale shows that the flame consists of two portions. The primary portion around the axis spreads downstream to 70 diameters with its biggest radial dimension of $y=2.5d$ at approximately 20 diameters. The largest scale dimension, $L_x=22$ mm, is found at 50 diameters with the scale decreasing rapidly to 70 diameters. Comparison with a cold jet to 20 diameters shows marked similarities.

The secondary portion of the flame, further from the axis, shows increasing dimensions even beyond 70 diameters and $y=3$ to 4 diameters, even though increasing temperature will not entirely account for this.

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Matsumoto, R., Fujiwara, T., and Kondo, J. (University of Tokyo, Tokyo, Japan) "Nonsteady Thermal Decomposition of Plastics," *Twelfth Symposium (International) on Combustion*, Pittsburgh, The Combustion Institute, 515–524 (1969)

Sections: G, H
Subjects: Thermal decomposition; Plastics

Reviewed by J. de Ris

This theoretical study considers the transient thermal decomposition (i.e., pyrolysis) of a phenolic nylon solid subjected to a constant surface heating rate. Although this particular study is directed toward the aerospace ablation problem with very high heating rates, similar techniques could be applied to the wood pyrolysis problem with the much lower heating rates produced by a fire.

The solid is regarded as a one-dimensional semi-infinite medium which suddenly receives a constant surface heat flux. As the resulting thermal wave propagates into the solid, it causes the virgin material to decompose into gaseous volatiles and residual char. The volatiles flow out through the char, which is created at the pyrolysis zone and gradually consumed at the surface by oxidation.

The mathematical model, which describes the above physical processes, has three parts: (1) oxidizing surface, (2) char zone, and (3) the combined virgin and pyrolysis zones. Equations for mass conservation and energy conservation are formulated for each zone.

The surface oxidation is regarded as an Arrhenius rate-controlled process which is sensitive to the surface temperature. The heat released by this process increases the effective heat transfer into the solid; while the energy lost by surface radiation decreases the heat transfer.

The char zone is regarded as a constant density porous medium through which gas flows toward the surface. This char tends to insulate the pyrolysis zone from the surface. The char zone energy equation employs a variable thermal conductivity; however, the specific heats for both char and volatiles are regarded as constant.

The pyrolysis and virgin zones are treated together. The energy equation includes the effects of conduction, gaseous convection, endothermic pyrolysis, and transient processes. The pyrolysis process is regarded as a single endothermic overall first-order Arrehenius reaction,

$$\dot{m}_p''' = \rho a_p \exp(-E_p/RT),$$

where $\dot{m}_p'''$ is the pyrolysis mass volatilization rate per unit volume, ρ the solid density, a_p the pre-exponential factor, E_p the activation energy, and Q_p the endothermic heat of pyrolysis. The experimental results of Nelson[1] and Madorsky[2] provide the values: $a_p = 4.2 \times 10^5\ \text{sec}^{-1}$, $E\text{s} = 72$ Btu/mole, and $Q_p = 126$ Btu/lb. The actual pyrolysis process probably involves several competing multistage reactions; however, this simplified overall model should be adequate for engineering applications.

This problem, with appropriate boundary conditions, is solved numerically on a computer. The solution seems to agree fairly well with experiment; however, there is some doubt as to the experimental heat flux conducted into the solid. Correct orders of magnitude are predicted for the surface temperature, surface regression velocity, pyrolysis front velocity, and char layer thickness.

The apparent success of this ablation study is encouraging for the problem of wood pyrolysis in fires. Such a quantitative solution to the wood pyrolysis problem appears vital to the understanding of destructive fire behavior.

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Merzhanov, A. G., Slutsker, B. M., and Shteinberg, A. S., "Thermal Decomposition and Thermal Explosion of Volatile Explosives," *Physics and Combustion of Explosion* 4, 540–547 (1968). In Russian.

Sections: G, A
Subjects: Explosion; Explosives; Thermal decomposition

Authors' Summary—Translated by L. Holtschlag

An analysis is made of the effect of evaporation on the macrokinetics of the thermal decomposition of a volatile explosive (a liquid) in an open vessel in the case of zero and first-order reactions. The kinetics of loss in weight of the liquid were examined in a constant-temperature thermogravimetric experiment. Thermal explosion was considered for simplicity in the case of equal temperature in the entire volume at each instant of time. A formula is derived for the critical conditions of thermal explosion, relating the temperature of the ambient medium, the reduced heat transfer and the temperature of the liquid at the explosion point. The characteristic dependence of steady-state heating on the parameters of the process is illustrated by a diagram for a model liquid.

Nii, R. (Fire Research Institute of Japan, Tokyo, Japan) "Burning Characteristics of Japanese Cigarets on Several Conditions," *Report of Fire Research Institute of Japan* 6 (1) 12, (August 1955)

Section: G
Subjects: Burning characteristics; Cigarets; Japan

Author's English Summary

The measurement of the maximum burning temperature of Japanese cigarets which are burning naturally or aspirated intermittently (what is called smoking) fixed horizontally, was done previously in the Central Research Institute of the Japan Monopoly Public Corporation, and so on.

But the only data on the conditions as mentioned above is not sufficient to make use of in fire research. Moreover, there is no investigation on the conditions other than those mentioned above. But the author felt keenly the importance of the investigation of burning characteristics of Japanese cigarets on several conditions by the fact that the fire caused by the burning cigaret is counted up in every year as one of the principal causes of fires in Japan; for example, among 25,677 total fire accidents, 1833 were caused by the burning cigarets in 1953.

From the viewpoint of fire research the experiment was carried out with four kinds of Japanese cigarets; *Golden Bat*, *Shinsei*, *Hikari*, and *Peace*. The results of the experiment are as follows:

(1) The maximum burning temperature (°C) and burning velocity (mm/min) at natural burning of Japanese cigarets fixed horizontally are shown in Table 1.

(2) The maximum burning temperature of Japanese cigarets which are fixed horizontally and burning aspirated continuously, increases a little as the aspirating pressure (in mm Aq.) increases until the aspirating pressure attains to a certain value, but is constant temperature at more than the certain value of the aspirating pressure. The mean burning velocity increases linearly as the aspirating pressure increases. It could be found that the aspirating effects do not contribute to the burning temperature of the cigaret but do contribute greatly to the burning velocity.

(3) Effect of the blower's wind on the burning characteristics of a Japanese cigaret, *Peace*:

(a) When the wind direction is parallel to the burning direction of cigaret, the mean burning velocity (in mm/min) increases as the mean wind velocity (during 5 min) (since then the author calls this only wind velocity) increases from 0 to 1 m/sec or so and then begins to decrease as the wind velocity exceeds 1 m/sec or so. The probability of the burning cigaret going out half-burned increases as the wind velocity exceeds 1.5 m/sec. The burning cigaret went out half-burned without fail when the wind velocity exceeded 3 m/sec.

(b) When the direction is vertical or antiparellel to the burning direction of cigaret, the burning cigaret went out half-burned without fail at the velocity of more than 1.4 m/sec.

(c) The time taken until the burning cigaret in wind goes out half-burned was about 3 to 4 min.

Novikov, S. S., Pokhil, P. F., and Riazantsev, Iu. S. "Current Concepts of the Combustion Mechanism of Condensed Systems," *Physics of Combustion and Explosion* **4,** 469–481 (1968) In Russian.

Section: G
Subjects: Combustion; Condensed systems; Review

Authors' Summary—Translated by L. Holtschlag

This review reports attempts to systematize and correlate the extensive experimental data on the combustion mechanism of condensed systems published in the

Soviet and non-Soviet literature in recent decades. The basis for this effort is the thermal theory of flame propagation developed by Soviet scientists, particularly N. N. Semenov and Ia. B. Zel'dovich. A comparison is made and a discussion is given of the experimental data on the various combustion characteristics of condensed systems, such as burning rates versus pressure and initial temperature, the structure of the temperature profile in the combustion zone, the heated layer and the heat-release zone in the k-phase, stable burning units, non-stationary burning rate and the special features of the burning mechanism of composite mixtures. The conclusions are: the burning process is multistage; for nonvolatile condensed systems, exothermic chemical reactions play an essential role in the heat balance of the condensed phase; the combustion zone has three heat-release maxima, the greatest being in the fizz zone close to the burning surface; a necessary stage in the burning process is dispersion of the material; the chemical reactions in the luminous flame zone, and partly in the fizz zone, may take place inductively, without affecting the burning rate; the pressure-dependence of the burning rate may be complex; the burning-rate dependence on the initial temperature is linear or piecewise linear; combustion of composite systems has a number of special features; and finally, there is no complete theory describing all the experimental data.

Price, R. B., Hurle, I. R., and Sugden, T. M. ("Shell" Research Ltd., Thornton Research Centre, Chester, England) "Optical Studies of the Generation of Noise in Turbulent Flames," *Twelfth Symposium (International) on Combustion* Pittsburgh, The Combustion Institute, 1093–1102 (1969)

Section: G
Subject: Noise in flames

Reviewed by F. Falk

Noise generation in turbulent flames is described by these authors as originating from monopoles which are an assembly of burning elements, the sizes and positions of which change continually, with each element leading to an increased volume of heated gas. Based on this model a simple acoustic theory, derived previously,[1] predicted that the far field pressure in the radiated sound waves during combustion should be proportional to the second derivative of the volume with respect to time, that is, proportional to the first derivative of the rate of combustion. In this paper the intensity of emission of C_2 radicals in the reaction zone was measured optically to determine changes in rate of combustion. Sound pressure measured with a conventional microphone agreed with those inferred from the optical technique.

If pressure measurements are restricted to a frequency band in which the retarded times for the waves from different elements are small compared with component quarter periods, the total instantaneous sound pressure is given by

$$p(t) = \sum_{n} p_i(t) = (\rho/4\pi d)(E-1)[dQ/dt]_{t-\tau} \qquad (1)$$

and the root-mean-square values are related by

$$p_{\mathrm{rms}}=(\rho/4\pi d)(E-1)[dQ/dt]_{\mathrm{rms}},$$

where $\rho=$ the density of the surrounding medium;
$d=$ the distance from the source;
$E=$ the volumetric expansion ratio;
$t-\tau=$ retarded time, where τ is the time required by the sound wave to propagate from the source to the point of measurement; and
$Q=$ the total volumetric rate of combustion in the flame.

In addition, since it was previously shown that the rate of combustion is proportional to the intensity of C_2 emission from the reaction zone,[2] then $[dQ/dt]=k[dI/dt]$, where "I" is that measured intensity and k is the slope of the straight line found by plotting values of the mean intensity of emission of C_2 against the mean flow rate of combustible mixture down the burner tube.

The authors measured the light emission of C_2 in the (0, 0) band with a head at 5165 Å as well as measuring directly the sound pressure for various flames and compared waveforms and measured and inferred pressures to confirm their assumptions.

For a turbulent premixed ethylene/air flame in which conditions of turbulence were varied, it was found that p_{rms} was proportional to $[dI/dt]_{\mathrm{rms}}$, as predicted and, in fact, the proportionality was $[\rho(E-1)k/4\pi d]$, as expected.

For a turbulent diffusion flame of an 84% H_2/16% CH_4 mixture burning in air, a correlation was sought between P/t and $(dI/dt)/t$ waveforms. When allowance was made for the transit time for the sound wave to reach the microphone, good qualitative agreement was shown. Further, it was found that above a certain flow rate (200 cm^3/sec) the intensity of emission was linear with flow rate, i.e., the volume of fuel, Q_7, was equal to $k'I+C$. It was assumed that the burning took place at stoichiometric so that k [from $d\theta/dt=k(dI/dt)$] was equal to $k'k''$ where $k''=[Q_f+Q(\text{stoichiometric})]/Q_f$. From this a sound pressure waveform was inferred from the spectroscopic measurements and was found to be in very good agreement with the measured pressure waveform, thus justifying the assumption of stoichiometric combustion.

For a liquid-fuel spray flame the continuum radiation limited the optical technique. Nevertheless, a good correlation was found between the P/t and $(dI/dt)/t$ waveforms.

In addition to demonstrating that the main sources of sound in turbulent flames are monopoles, this report presents some basic information on the nature and structure of turbulent flames. A plot of C_2 emission intensity versus flow rate for ethylene/air premixed flames for three different burners under varying conditions of pipe-flow turbulence show a common straight line, even though with each burner the flame was laminar at the lower flow rates. These observations are consistent with the wrinkled flame model of turbulent combustion rather than a difference in mechanism in turbulent and laminar flames.

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Raizberg, B. A. "Physical Principles and Mathematical Model of the Process of Flame-Front Propagation Over the Surface of a Solid Propellant Upon Ignition," *Physics of Combustion and Explosion* **4,** 568–578 (1968). In Russian.

Section: G
Subjects: Convective heating; Flame propagation; Noise generation; Optics; Solid propellant

Author's Summary—Translated by L. Holtschlag

A rather complete and rigorous description is given of the physical phenomena observed during the period of flame-front propagation along the surface of an ignited charge of solid propellant. The charge is ignited by introducing hot ignition products into one end of the perforation, heating the surface of the perforation and gradually igniting it. The assumptions are that a section of the surface near the inlet is ignited first, and then the boundary of the ignited and not ignited portions of the surface propagates along the perforation. The problem consists in determining the rate of propagation of the flame front with time. Two basic cases are examined: the charge is heated primarily by convection and radiative heating by particles in the combustion products.

Staff (Safety Research Center, U. S. Bureau of Mines, Pittsburgh, Pennsylvania)* "Research and Technological Work on Explosives, Explosions, and Flames, Fiscal Year 1968," *U.S. Bureau of Mines Information Circular 8442* (1970)

Sections: G, H, I
Subjects: Explosion research; Explosives research; Flame research; Technology of explosives and flames

Staff Abstract

Research and technologic work on explosives, explosions, and flames: fiscal year 1968, by Staff, Safety Research Center.

* Safety Research Center (formerly Explosives Research Center), Bureau of Mines, Pittsburgh, Pa. On July 1, 1969, the Explosives Research Center and the Health and Safety Research and Testing Center merged to form the Safety Research Center.

Togino, S., Miyata, R., and Ishizaka, K. (The Fire Research Institute of Japan, Tokyo, Japan) "On the Water Hammer in Fire Hose," *Journal of the Fire Research Institute of Japan* 6 (1), 12–17 (August 1955)

Sections: G, H
Subjects: Fire hoses; Hydraulics; Water hammer

Authors' English Summary

Fire hose, in practice, is subject to occasional danger of rupture due to water hammer pressure caused, for instance, by sudden closing of a shut-off nozzle or by a car passing over the hose line. The authors' work reported here was made to clarify the nature of the phenomenon cited and thereby furnish basic data usable in testing hose for pressure. In the first stage of the work, both the wave form and the propagation velocity of pressure surge in hose line were measured. Pressure pick-up heads employed were of wire strain gauge type (Fig. 2), the outputs of which were recorded by both pen and optical oscillographs (Fig. 3b). An example of pressure surge record is shown in Fig. 4. The crest values of pressure rise (Δp) measured of 2.5-in. unlined linen and rubber-lined nylon–cotton hoses are plotted against mean flow velocity (ν_0) in Fig. 5. Applying Allievi's formula $\Delta p = c\rho\nu_0$ (c = the propagation velocity of pressure wave in m/sec, and ρ = the density of water in kg sec^2/m^4) to our results, we get $c = 262$ m/sec for linen and $c = 118$ m/sec for rubber-lined hoses, respectively, while the actual measurements of c give 250 m/sec (linen) and 110 m/sec (rubber-lined). This shows that Allievi's general formula is well applicable to water hammer in fire hose. In the second stage, attempt was made to estimate the water hammer pressure rise on the basis of the expressions:

$$c = (J/\rho)^{1/2}, \qquad 1/J = 1/K + 1/K'$$

where K = the bulk modulus of hose (kg/m^2) and K' = bulk modulus of water = 2.07×10^8 kg/m^2. K is computed from measured values for both elongation and expansion of hose under pressure. The values of c calculated by this method were 270 m/sec for linen hose and 108 m/sec for rubber-lined hose, respectively, showing fairly good agreement with the above-mentioned direct measurement. Thirdly, another indirect method to estimate Δp was tried, in which only c was measured with pressurized hose line, a pressure surge being applied by knocking a piston attached to one end of hose (Fig. 7). This method, however, tends to give values for c rather greater than those obtained by foregoing two methods (Fig. 8).

Thomas, P. H. (Joint Fire Research Organization, Borehamwood, England) "On Thermal Theories of Fire Spread along Thin Materials," *Joint Fire Research Organization Fire Research Note No. 774* (August 1969)

Sections: G, H, I
Subjects: Fire spread; Surface burning; Thermal theory; Thin materials

Author's Summary

Flame spread along a thin material or along the surface of a thick material is one of the features of fire spread, and, with the possible exception of the calculation of

radiation transfer across gaps between combustible materials, the one which has attracted perhaps the most theoretical attention.

In such theories account must be taken of the energy balance and, although there are conditions when this is not sufficient to account for all features of the spread, e.g., the generation of flammable gases can sometimes be a critical factor, the heating of the unburnt fuel ahead of the fire is frequently the controlling factor. In discussing this heating theoretical problems sometimes arise and this paper refers to some of those in the theory of smouldering of Kinbara, Endo, and Sega.

Williams, G. C., Hottel, H. C., and Gurnitz, R. N. (Massachusetts Institute of Technology, Cambridge, Massachusetts) "A Study of Premixed Turbulent Flames by Scattered Light," *Twelfth Symposium (International) on Combustion*, Pittsburgh, The Combustion Institute, 1081 (1969)

Section: G
Subjects: Scattered light; Premixed flames; Turbulence; Turbulent flames

Reviewed by F. Falk

In the work summarized in this report, the authors intended to develop and demonstrate a technique for the quantitative study of the effects of upstream turbulence on premixed gaseous flames. An optical probe was used to measure the concentration of sub-micron particles in the stream. These had been injected in known concentration in the cold stream. Under the experimental conditions of constant pressure and constant number of moles of gas, the particle concentration was inversely proportional to the local absolute temperature.

Experimentally, particles were added to a stream of methane and air by the controlled combustion of magnesium ribbons. The unburned gas, containing the magnesium oxide particles, was passed through a calming chamber and nozzle and then through a biplane grid and dust to produce a stream of known and adjustable turbulence. A 3-in.-diam wire ring which was used to stabilize the flame added little additional turbulence to the stream. No dilution of the combustion gases occurred in the region where data were taken.

Particle density was determined by light scattering. For the concentrations used, the light scattered was directly proportional to the concentration of the particles. A 0.1-in.-diam beam of a collimated d.c. mercury arc lamp illuminated the flow field and the light scattered at 90 degrees by a 0.1-in. length of the beam was measured by a focused photomultiplier tube. A narrow band filter was used to eliminate all but the 5461 Å light from the arc. The electronic circuit response was linear to 10 kHz.

Typical oscilloscope traces indicated that in general the burning zone was made up at rapidly oscillating regions of either fully burned or completely unburned gases. Higher resolution traces showed a measurable transition time.

The cold stream velocity, turbulent intensity, and scale of turbulence were varied to examine their effect on the observable fluctuations in the burning zone. Data were recorded over a range of vertical and radial positions.

The data obtained were consistent with the wrinkled flame model. The mean transition speeds (i.e., the ratio of probe size to transition time), averaged over all positions, were found to approximate the cold-flow nozzle velocity. The scale of the burned fluctuations versus time-average volume percent burned increased along a radius from regions of low volume percent burned to regions at high volume percent burned, showing a very rapid increase as combustion approached completion. Fluctuation frequency reached a maximum versus volume percent burned in the central regions of the flame brush, which correspond to the most probable positions of the wrinkled flame front.

Measured transition velocities varied linearly with volume percent burned and changed by about 40 percent from 0 to 100 volume percent burned, with the higher wave velocity in the burned region. This is also consistent with the wrinkled flame hypothesis. The author pointed out that the measured transition speeds may be interpreted as wave velocities, the measured scale at 50 volume percent burned as one-half the wavelength, and the width of the flame brush as twice the wave amplitude.

The average wave velocity was determined by the cold-flow velocity and was unaffected by other upstream properties. The distribution of wave velocities at radial positions also was scaled to the cold-flow velocity. Wavelengths and amplitudes within the flame brush were essentially independent of upstream turbulence.

Volumetric burning rates were estimated from the radial variation of mean volume percent burned. A local average rate of 240×10^6 kcal/m^3 hr was found at a position of 50 percent mass burned, for mean conditions. The gross volumetric burning rate was estimated to be 125×10^6 kcal/m^3 hr.

The authors refer to a somewhat similar study by Karolvitz[1] in which an unshielded negatively charged probe was used to indicate the presence or absence of high-ion concentrations in local regions of a combustion wave. As a function of radial position, the fluctuation frequency and percentage of time in contact with the combustion wave were determined. The latter is similar to the time-averaged volume percent burned. Although Karlovitz's conditions are not similar to those of the present study, the results fall within the general pattern found in this work. This seems to indicate that both techniques measure the same kind of fluctuation frequency and volume percent burned.

The authors have demonstrated in this report that their light scattering technique provides high frequency response measurements of local temperatures in premixed turbulent combustion because of the information which can be deduced with regard to velocity and scale of temperature fluctuations.

In addition to presenting this new technique, the authors demonstrate that all data obtained with this technique in the system studied are consistent with the wrinkled flame model. Further, high speed photographs of the flame indicated a structure and shape consistent with that deduced from the light scattering measurements.

Reference

1. Karlovitz, B., *et al.:* Fourth Symposium (International) on Combustion, Williams and Wilkens, p. 613 (1953).

Zelikman, E. G. "Degenerate Regimes of Thermal Explosion in Autocatalytic Reactions," *Physics of Combustion and Explosion* **4**, 563–567 (1968) In Russian.

Sections: G, H, I, B
Subjects: Autocatalytic reactions; Degenerate regimes; Ignition; Thermal explosion

Author's Summary—Translated by L. Holtschlag

The characteristics of degeneration of thermal explosion in catalytic reactions close to and far from the ignition point were analyzed in a broad range of the parameters β and γ, namely, small values (nondegenerate explosion), medium values (degenerate), and large values (highly degenerate). A lower limit for the degenerate regime was obtained at various values of the autocatalytic criterion (γ_0) in the region considerably above the ignition point, where the process may be considered as adiabatic.

H. Chemical Aspects of Fires

Kondrat'ev, V. N. "Kinetics of the Combustion Reaction of Gas-Phase Systems," *Physics of Combustion and Explosion* **4**, 446–454 (1968) In Russian.

Sections: H, I, G
Subjects: Combustion; Elementary reaction; Gas phase; Hydrocarbon; Kinetics

Author's Summary—Translated by L. Holtschlag

The kinetics of chemical reactions occurring during high-temperature combustion of gas systems are discussed, particularly the burning of hydrocarbon propellants in nozzles or at nozzle throats of rockets moving in atmosphere. Various aspects are discussed, including flames and slow isothermal burning. It is found that calculations based on the rate constants of elementary chemical reactions are unreliable. Even in simple chemical systems the high temperature inhibits solution of the problem of chemical kinetics. Further work in developing the theory of elementary reactions is necessary, since the theoretical and experimental research has been poorly coordinated. The mechanism of hydrocarbon combustion can be studied more thoroughly on the basis of the sufficiently well-known hydrogen burning mechanism. It is emphasized that the presently available information on the chemical kinetics of combustion processes is inadequate to meet the needs of modern technology. Several research directions are indicated.

Mingle, J. G. and Boubel, R. W., "Proximate Fuel Analysis of Some Western Wood and Bark," *Wood Science* 1 (1), 29–36 (1968)

Sections: H, G, N
Subjects: Bark; Fuel analysis; Proximate analysis; Sawdust; Western; Wood

Reviewed by F. L. Browne

For the aid of engineers who use wood waste for fuel, ASTM test D–271–48 "Laboratory Sampling and Analysis of Coal and Coke" was modified for the proximate analysis of wood and bark. Analysis for moisture, volatile matter, ash, and fixed carbon (charcoal) allows calculation of the heat required to drive off water, the residue to be disposed of, and the proportion of primary to secondary combustion air to minimize smoke and air pollution.

Sawdust from western woods was collected at the head rig saw at the mills in moisture-impervious plastic bags. Chunks of bark from debarking operations were collected similarly and then comminuted with a sabre saw to include both cambium and cork layers. Further grinding was unnecessary.

To determine moisture 25 ml silica crucibles with lids, dry after use for the ash test, were weighed, filled to within $\frac{1}{8}$ in. of the top with 3 to 6 grams (according to density) of wet sawdust, weighed, and dried 16 hr (or overnight) with lids off at

TABLE I
Proximate Analysis of Western Woods and Barks

		Percent by weight (average of 3 determinations)				
		Moisture		Volatile matter	Charcoal	Ash
Species	Type	Wet basis	Dry basis	Dry basis	Dry basis	Dry basis
Hemlock	Sawdust	52.2	109.2	84.8	15.0	0.2
Hemlock	Bark	25.0	33.3	74.3	24.0	1.7
Douglas fir	Sawdust	39.6	65.6	86.2	13.7	0.1
Douglas fir	Old growth bark	8.2	8.9	70.6	27.2	2.2
Douglas fir	2nd growth bark	49.3	97.2	73.0	25.8	1.2
Grand fir	Bark	33.7	50.8	74.9	22.6	2.5
White fir	Sawdust	64.2	179.3	84.4	15.1	0.5
White fir	(Shasta Red) bark	18.2	22.2	73.4	24.0	2.6
Ponderosa pine	Sawdust	54.1	117.9	87.0	12.8	0.2
Ponderosa pine	Bark	13.3	15.3	73.4	25.9	0.7
Alder	Mixed sawdust, bark	36.3	57.0	84.9	14.5	0.6
Alder	Bark	28.8	40.4	74.3	23.3	2.4
Redwood	Sawdust	51.4	105.8	83.5	16.1	0.4
Redwood	Bark	12.2	13.9	71.3	27.9	0.8
Cedar	Sawdust	43.5	77.0	77.0	21.0	2.0
Cedar	(Red) bark	30.9	47.4	86.7	13.1	0.2
Cedar	(Incense) bark	20.0	25.0	77.4	22.0	0.6

100° to 104°C in a model 420 NAPCO oven with circulating air dried by sulfuric acid, then cooled in a desiccator and weighed.

To determine volatile matter the 10 ml platinum capsule and Hoskins furnace specified in ASTM-D-271-48 were used. The capsule, previously heated at 950°C for 2 min, cooled in a desiccator, and weighed, was filled with sawdust within $\frac{1}{2}$ to $\frac{3}{8}$ in. of the top, weighed, and then slowly warmed to evolve volatile matter by lowering into the furnace until the top of the crucible was level with the top of the furnace for 2 min for wet or 1 min for dry samples. Luminous flames revealed the distillation of most of the volatile gases during this "flaming period." Next the capsule was lowered to the bottom of the furnace for 6 min ("soak period"). The capsule was then removed from the furnace, cooled in a desiccator, and weighed.

To determine ash a tarred 25 ml silica crucible was filled within $\frac{1}{8}$ in. of the top with 4 to 6 grams of wet sample, weighed, and placed in the center of a muffle furnace preheated to 750°C for 30 min for sawdust of less than 1.0% ash content to 45 min for bark or dust of high ash content. High ash content samples were removed from the furnace after 39 min, stirred to break up any caking, and returned to the furnace for the remaining 15 min. They were then removed, cooled in a desiccator, and weighed. During the heating the furnace door was kept one-third open until flaming subsided, then closed to $\frac{1}{4}$ in. crack across the top, and after 15 min closed completely to avoid losses of sample in the turbulent flames.

Charcoal was determined by difference.

Results for a number of western woods and barks appear in the table.

Tucker, B. G. and Mulcahy, M. F. R. (CSIRO Division of Mineral Chemistry, Coal Research Laboratory, Chatswood, N.S.W., Australia) "Formation and Decomposition of Surface Oxide in Carbon Combustion," *Transactions of the Faraday Society* **65,** 274–286 (1969)

Section: H
Subjects: Carbon; Combustion; Decomposition; Formation; Surface oxide

Reviewed by G. S. Pearson

This paper describes a gravimetric study of the formation of surface oxide on graphitized carbon black by reaction with oxygen at 500°C and the subsequent desorption of the oxide as CO at 600°–750°C. The experiments were made with Graphron usually referred to as "graphitized" carbon black but, in fact, this is "turbostratic" carbon with a high degree of order in the basal plane but considerably less in the C direction. The surface area as supplied was 80.5 $m^2 g^{-1}$ and emission spectroscopy showed an impurity level of 150 ppm of which 100 ppm were Ca. All samples were burned off by at least 5% in 50 Torr oxygen at 650°C before carrying out kinetics experiments. Numerous experiments were made on a single sample.

It was found that surface oxide is formed exclusively during the initial transient period of fast combustion observed by previous workers. A brief investigation of the kinetics of steady combustion at 457°–525°C and $p_{O_2}=20$ torr gave the result

$$-(dC/dt)_s \propto p_{O_2}^{\sim 0.5} \exp[(-43000\pm 200)/RT]$$

where $(dC/dt)_s$ is the rate at which carbon is burned to gaseous products and p_{O_2} is the constant oxygen pressure. This is in good agreement with previous work. The CO/CO_2 ratio of the combustion products at 500°C, 20 torr was 0.5, distinctly lower than that of the desorption products which gave a CO/CO_2 ratio of 3 for desorption of the first 4% at 550°C, of 10 for desorption of 25–50% at 650°, and of 50–200 for desorption of the second 50% at 950°C.

The kinetics of desorption of the oxide remaining on the surface after a period of steady combustion followed the Elovich relation

$$w = a + b' \log t$$

where w is the weight desorbed at time t, and a and b' are constants at constant temperature. The Elovich plots are used to obtain values of $d\theta/dt$, where θ is the number of active sites occupied at any stage of desorption relative to the number occupied during steady combustion, i.e., before desorption is begun, from the relation

$$-d\theta/dt = b/t$$

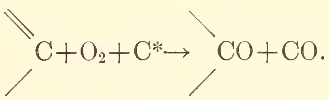
where b is the slope of the Elovich plot. Then Arrhenius plots of the kinetics of desorption follow the relation

$$-d\theta/dt = D_\theta \exp\{-[E_1 + \beta(1-\theta)]/RT\}$$

where $\log_{10} D_\theta = \log_{10} D_1 + \alpha(1-\theta)$ and D_1, E_1, α and β are constants. Values of 70 and 57 kcal $mole^{-1}$ were found for E_1 with two samples that had a lower and higher burn off, respectively. The corresponding values of β were 43 and 47 kcal $mole^{-1}$.

At 500°C combustion occurs at an appreciable rate but desorption of the surface oxide does not. Hence, combustion does not occur by adsorption-desorption of the oxide at this temperature.

In the light of microscopic studies by Thomas,[1] it is proposed that the formation of thermally-stable surface oxide at lower temperatures represents an arrested stage of the reaction at the armchair $\{112l\}$ face; this reaction generates surface oxide and CO simultaneously from "stable" and "labile" carbon atoms, respectively:



At high temperatures the oxide is desorbed, thus regenerating a labile carbon and allowing combustion to continue, but at low temperatures this does not occur and reaction ceases when all the labile atoms have been consumed. The attack of an oxygen molecule after desorption of CO at high temperature, 975°C, is considered to remove the labile C atom of the armchair edge as CO and an O atom is adsorbed. Reaction at the zigzag edges of the crystal followed by desorption of an O atom would not produce a labile C atom. It is therefore assumed that reaction at zigzag sites does not produce a stable surface oxide.

Final proof of these postulates is not available but they are discussed in the light of this and other evidence.

Reference

1. Thomas, J. M.: Chemistry and Physics of Carbon, Vol. 1, P. L. Walker, Ed., p. 121, Marcel Dekker, New York, 1965.

Woolley, W. D. (Joint Fire Research Organization, Borehamwood, England) "A Study and Toxic Evaluation of the Products from the Thermal Decomposition of PVC in Air and Nitrogen," *Joint Fire Research Organization Fire Research Note No. 769* (July 1969)

Section: H
Subjects: Combustion products; Gas chromatography; Hydrogen chloride; Mass spectrometry; Phosgene; Plastics; Poly(vinylchloride); Pyrolysis; Thermal decomposition; Toxic gas

Author's Summary

The products from the thermal and thermal-oxidative decomposition of PVC from 300° to 500°C have been studied by gas chromatography and mass spectrometry. Approximately 75 products have been detected up to naphthalene by gas chromatography and shown to consist essentially of aromatic and aliphatic hydrocarbons. Weight loss experiments and time resolved chromatography indicate that these products are generated mainly during dehydrochlorination. The products are modified slightly by the presence of oxygen but no oxygenated organic materials have been detected. The products, apart from carbon monoxide, are shown to have little toxicity in relation to the hydrogen chloride. Difficulties encountered with the analysis of phosgene are recorded and some preliminary results from a series of specific phosgene experiments are given.

I. Physical Aspects of Fires

Baldwin, R. and North, M. A. (Joint Fire Research Organization, Borehamwood, England) "Stress-Strain Curves of Concrete at High Temperature—A Review," *Joint Fire Research Organization Fire Research Note No. 785* (October 1969)

Section: I
Subjects: Concrete; High temperature; Review; Stress–strain

Authors' Summary

This note reviews some data on the effect of temperatures (up to 700°C) on the relationship between stress and strain for concerte under compression. It is shown that if all the data are normalised to the stress and strain at the peaks of the various stress–strain curves for different temperatures (the compressive strength) the curves are virtually the same.

J. Meteorological Aspects of Fires

Huffman, K. G.,* Welker, J. R., and Sliepcevich, C. M. (University of Oklahoma Research Institute, Norman, Oklahoma) "Interaction Effects of Multiple Pool Fires," *Fire Technology* 5 (3), 225–232(1969)

Sections: J, D, I
Subjects: Burning rates; Flame height; Interaction; Multiple fires; Pool fires

Reviewed by K. Sumi

The interaction of multiple fires from liquid pools burning in close proximity to one another was examined to determine the effect on the burning rate, heat feedback, flame height, and flame trailing. Methanol, acetone, hexane, cyclohexane, and benzene were burned in several sizes and spatial arrangements of burners. Circular burners, 4 in. in diameter, were used in the 13 burner pattern with 1 burner at the center, 4 at an intermediate position and 8 at the periphery. Burners with diameters of 2, 4, and 6 in. were used in a 9-burner pattern with 1 burner at the center and 8 at the periphery.

Burning Rates

The multiple fires change progressively from individual flames with no interaction to individual interacting flames and finally to fully merged flames as the separation distance decreases. At large separation distances, the burning rates for the center burner and the outer burners are about the same. As the burners are brought closer together, the burning rate for the center burner increases and peaks faster than that for the outer burners. Both approach a common value, however, at the closest separation distance. The maximum burning rate for the center burner occurs at the onset of merging.

Heat Feedback

The burning rate of liquid fuel is determined by the rate of heat feedback from the fire to the fuel. The total heat feedback is the sum of conductive, radiative, and convective terms. In the present tests, the conductive term was minimized by tapering and insulating the burner rims. Although there may have been a small increase in the convection coefficient due to the interaction effects, the authors believe that increases in burning were primarily due to increases in radiative feedback. Two generalized correlations of burning rate data for the 9-burner pattern were made—one for the center burner alone, and the other for tle average burning rate of all 9 burners combined. The experimental data provide a means for estimating the burning rates of interacting fires when the burning rate from a single pool and the fuel properties are known. Caution must be used in extrapolating the data to larger pool sizes because the burning rate of larger fires would not increase significantly due to interaction effects.

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Flame Height

Thomas[1] developed a relationship between flame height and burning parameters for wood crib fires, and Waterman *et al.*[2] applied this relation to data from multiple wood crib fires. The latter took the fuel source dimension to be that of the multiple crib array rather than that of a single crib.

The flame height correlation suggested by Thomas was applied to the liquid interacting fires. The flame heights were about the same or slightly larger than those of Thomas, but they were significantly larger than those of Waterman.

Flame Trailing

The flame trailing effect exhibited by windblown pool fires has been described previously.[3] The induced wind caused the same effect in the interacting fire tests. The relationship found in the earlier wind tunnel tests was found to be valid for the interacting fires.

References

1. Thomas, P. H.: "The Size of Flames from Natural Fires", Ninth Symposium (International) on Combustion, Academic Press, pp. 844–859, 1963.
2. Waterman, T. E., Labes, W. G., Salzberg, F., Tamney, J. E., and Vodvarka, F. J.: "Prediction of Fire Damage to Installations and Built-Up Areas from Nuclear Weapons," Final Report, Phase III, Experimental Studies, Appendices A–G, IIT Research Institute Report for National Military Command System Support Center, Contract No. DCA–8 (November, 1964).
3. Welker, J. R., and Sliepcevich, C. M.: "Bending of Windblown Flames from Liquid Pools", Fire Technology *2*, (2) 127 (May 1966).

Simard, A. J. (Forest Fire Research Institution, Department of Fisheries and Forestry, Ottawa, Canada) "Variability in Wind Speed Measurement and Its Effect on Fire Danger Rating," *Information Report FF-X-19* (June 1969)

Sections: J, L
Subjects: Fire danger; Variability (wind speed); Wind speed

Author's Abstract

This paper analyzes wind speed and direction distributions obtained at nine forestry stations and nine airports across Canada. The effect of differences in the distributions on forest fire danger rating is discussed. The major finding is that forestry stations have a significantly lower average wind speed than airports and the difference between the two decreases as wind speed increases. This difference caused a considerably greater percentage of days to fall in the extreme fire danger class at the airports. The data did not permit the derivation of a function relating the wind speed ratio to the size of the clearing at the forestry station.

K. Physiological and Psychological Problems from Fires

Chambers, E. D. (Joint Fire Research Organization, Borehamwood, England) "Make Leicester Fire-Safe Campaign: False Alarm Statistics," *Joint Fire Research Organization Fire Research Note No. 777* (September 1969)

Sections: K, L
Subjects: Correlation; False alarm; Fire prevention; Fire statistics; Leicester; Publicity; Statistics; Time series

Author's Summary

False alarm statistics are examined for a period before and after a fire prevention campaign. Random variations make it difficult to see any effect, although there is a suggestion that false alarm calls from automatic detection systems may have decreased.

"Effects of Chronic Exposure to Low Levels of Carbon Monoxide on Human Health, Behavior, and Performance," *Report Prepared by the Committee on Effects of Atmospheric Contaminants on Human Health and Welfare, Division of Medical Sciences, National Research Council for the Environmental Studies Board, National Academy of Sciences and National Academy of Engineering. National Academy of Sciences Publication 1735* (*Standard Book Number 309-01735-1, Library of Congress Catalog Card Number 73-602110*) (*1969*)

Section: K
Subjects: Behavior; Carbon monoxide; Carboxyhemoglobyn; Chronic exposure; Hemiglobyn; Human health; Hyperoxya; Performance

Reviewed by A. Bidjinski

Members of the Committee

Arthur B. DuBois, University of Pennsylvania, *Chairman*
Rodney R. Beard, Stanford University
Bertram D. Dinman, University of Michigan
Leon Farhi, State University of New York at Buffalo
Robert E. Forster, University of Pennsylvania
John R. Goldsmith, Department of Public Health, State of California
Victor G. Laties, University of Rochester
Solbert Permitt, Johns Hopkins University
John H. Schulte, Ohio State University

For the Division of Medical Sciences

Charles L. Dunham, *Division Chairman*
Adam J. Rapalski, *Professional Associate*

Note on the Scope of the Report

"The Committee has evaluated current knowledge concerning the effects of carbon monoxide on man. This is not a bibliography; a bibliography is already available.* In preparing this report, the Committee did not attempt to review the interaction between carbon monoxide and other atmospheric contaminants. Possible effects when it is in combination with other contaminants in ambient air must be considered when establishing criteria for air quality."

Reactions of Carbon Monoxide with Heme Proteins—Robert E. Forster

Carbon monoxide reacts with the iron of porphyrin, and the reaction affects hemoglobin (Hb), myoglobin (Mb), cytochrome oxidase, cytochrome P_{450}, and hydroperoxidases. Of these only Hb is significantly affected by exposure to low levels of CO. The effect of CO on Hb is twofold. One, it combines with Hb to form carboxy hemoglobin (COHb), which is incapable of carrying oxygen from lungs to other tissues; two, by eliminating low concentration binding sites from Hb it shifts the effective O_2Hb dissociation curve to the left, making it relatively more hyperbolic. Although the affinity for O_2 is increased, the tissue cells are affected, because the local pO_2 must be decreased to remove given amount of O_2 from Hb. That probably is the reason why the effects of CO intoxication are slightly different than the effects of lowering pO_2 in atmosphere, e.g., at high altitudes.

Effect of Carbon Monoxide in the Presence of Abnormal Hemoglobins—Robert E. Forster

Carbon Monoxide Production by Organisms—Robert E. Forster

The physiological level of carboxyhemoglobin in human blood, when CO is totally absent from breathing air, is 0.4%. This is a result of normal production of CO, which in man proceeds at the rate of 0.42 ml/m. The main source of internally produced CO is degradation of hemoglobin, although other porphyrines contribute. The turnover rate of hemoglobin is such that most of internally produced CO in blood corresponds to Hb degraded—on a mole-per-mole basis. CO is also produced in plants and lower invertebrates and therefore it may be assumed that CO production is a widespread function of organisms.

Carbon Monoxide Oxidation by Organisms—Robert E. Forster

Oxidation of CO by living organisms does occur, but the rate of it is slow and the mechanism obscure.

Atmospheric Carbon Monoxide—Robert E. Forster

Uncontaminated air at sea level contains less than 0.1 ppm CO—practically the limit of accuracy of measurement. This represents a total of 5.2×10^{14} g of CO in the atmosphere. The estimated production of CO by combustion is about 2.1×10^{14}

* Cooper, A. G.: "Carbon Monoxide; a Bibliography with Abstracts." Public Health Service Publ. No. 1503. Washington, D. C.: U.S. Department of Health, Education, and Welfare, 1966. 440 pp.

g/year—about one-third of that in the atmosphere. No significant increase in atmospheric CO has been noticed, although an increase in atmospheric CO_2 has. The seas would dissolve only 3×10^{12} g of CO.* Therefore, some chemical process of removing CO from atmosphere must exist. A number of possible reactions in the atmosphere must exist. A number of possible reactions in the atmosphere have been considered, but neither individually nor collectively can they explain the rate of CO disappearance. Biological mechanism is a possibility, but none has been shown so far.

Tissue Hypoxia and Carbon Monoxide—Solbert Permutt and Leon Farhi

A normal man at sea level with an arterial pO_2 of 100 mm Hg will have carboxyhemoglobin saturation level of 9% when exposed to 70 ppm of CO long enough for the steady state to be reached. If there were no change in blood flow, Hb concentration, or alveolar ventilation, the venous pO_2 in various organ vascular beds would be lowered by 4–6 mm Hg. To produce a similar lowering of venous pO_2 in a person not exposed to CO, the blood flow or the concentration would have to be reduced by 20% to 40%. The arterial pO_2 would have to be lowered by 23% to 46% if Hb concentration and blood flow remained constant. These calculated results are in good agreement with the clinical observations that coronary blood flow in human subjects with COHb levels of 9% (the same level as in the hypothetical analysis) increased by 44% and still there was a slight drop in coronary sinus pO_2.

With smaller COHb levels, the effects on venous pO_2 will be proportionally smaller, and the requirements of changes in blood flow or Hb concentration to adjust venous pO_2 to normal will also be proportionally smaller.

Cumulative effects of CO exposure in persons who already have impairment of blood flow or alveolar ventilation should not be overlooked. High altitudes, chronic lung disease, anemia, decreased blood flow, pregnancy are only some of the cases that require detailed investigations.

Method of calculating venous pO_2 as a function of COHb concentration is presented.

Effects of Long-Term Exposure to Carbon Monoxide—Bertram D. Dinman

The existence of "chronic carbon monoxide intoxication"—characterized by variety of elusive symptoms, i.e., headache, fatigue, insomnia, mood disturbance, impairment of memory, confusion, digestive disturbances, cardiac symptoms, etc., remains scientifically unproven. There is, however, enough evidence to warrant a serious study, since most of the previous efforts have been epidemiologically unsound and have used unsophisticated techniques of medical evaluation. Of particular interest are changes in red cell mass and Hb concentration upon longtime exposure to low (50 ppm) levels of CO. There is some evidence to suggest that after initial response to CO exposure, continuous exposure leads to acclimatization, e.g., red-cell mass returns to normal. This problem requires further clarification.

Review of Electroencephalographic Data—Bertram D. Dinman

Available EEG data have so far been of little use in evaluating effects of exposure to low levels of CO. This is mainly due to the difficulties in interpretation of EEG

* Y. W. Swinnerton *et al.*: *Science* 167, 981–986 (1970).

measurements, subjective nature of these interpretations, and lack of statistical method of comparing results that often seem contradictory. The use of new computational techniques may partially overcome these difficulties. Limitations of this approach should be emphasized.

Behavioral Aspects of Carbon Monoxide Poisoning—Victor G. Laties, Rodney R. Beard, Bertram D. Dinman, and John H. Schulte

Exposure to CO begins to affect easily measured physiological factors (pulse rate, cardiac output, blood pressure, expiratory ventilation) only when CO concentartion is high enough to rise COHb levels to 28% to 30%. Even prolonged exposure to levels of CO that produce lower levels of COHb does not change simple physiological measurements that have been studied. However, measurable changes in some sensory thresholds occur at levels well below 28% COHb. Significant impairment in brightness discrimination was found at 4% COHb. Ability to solve mathematical problems which normally take an adult about 13 minutes was impaired at COHn levels up to 20%; however, another study which employed shorter tests showed no effect of CO levels that caused slightly higher COHb concentration. Ability to judge short intervals of time was affected by small doses of CO (from 50 to 250 ppm) with the number of errors directly proportional to CO concentration in air. The CO exposure was long enough to produce COHb level of only 2%.

Epidemiologic Appraisal of Carbon Monoxide Effects—John R. Goldsmith, Rodney R. Beard, and Bertram D. Dinman

Exposure to CO as community air pollutant will increase COHb concentration in man. The amount of the increase is reasonably predictable and must be considered in relation to exposures to CO in inhaled cigarette smoke and domestic exposures.

Exposures for 5 hours to 10 to 12 ppm of CO will increase COHb levels in nonsmokers by 0.5%. Thirty ppm of CO for 8 hours will produce on the average an increase in COHb of 5%. It may be considered established that even 0.5% increase in COHb appreciably impairs oxygen transfer to the tissues in nonsmokers.

Cigarette smokers have a median COHb level much higher than nonsmokers, 5.9%, compared to physiological level of 0.4%, and there is no agreement as to whether exposure of smokers to increased CO in the air adds appreciably to that figure, although there is some evidence to that effect.

Contamination of air in the city ranges from 5 to 60 ppm of CO. In certain occupational areas (garages) it is even higher. However, at the present time there is insufficient evidence of the existence of "the chronic CO intoxication syndrome," and, accordingly, there is no evidence that community air pollution exposure could produce any type of chronic effects.

There is some evidence that exposure to CO hastens the process of atherosclerosis, but at this point evidence is more suggestive than conclusive.

Increased Hb concentrations have been associated with longtime exposure to CO in some studies.

The available evidence suggests that daily average CO levels in excess of about 10 ppm may be associated with increased movability rates in patients hospitalized with myocardial infarction.

Possible correlation between CO exposure, COHb levels and motor vehicle accidents has been studied but results are also inconclusive, mostly due to poor controls. There is enough evidence, however, to warrant coordinated study, especially in view of the findings that COHb concentrations as low as 2% affect certain sensory thresholds.

Summary

The amount of CO in the atmosphere is estimated at 5.2×10^{14} g. Every year combustion produces about one-third of that amount. No significant increase in the overall concentration of atmospheric CO has been noted although it is a factor in community air pollution, where its concentration ranges from 5 to 60 ppm as compared to 0.1 ppm in "fresh" uncontaminated air at sea level. This raises two basic questions: (a) what happens to CO released into the atmosphere, and (b) what are the effects of longtime exposure to relatively low levels of CO on the population.

The answer to the first question is far from clear. A number of possible reactions in the atmosphere have been considered, but neither individually nor collectively can they explain the rate of CO disappearance. The question becomes even more intriguing in view of the findings of Y. W. Swinnerton *et al.* (Science *167*, 981–6 (1970)), that the oceans far from being a "sink" for CO are actually releasing it into the atmosphere. According to their study the concentration of CO in surface water at two locations on the Atlantic ranged from 10^{-5} to 10^{-4} ml/l, which is 10 to 100 times higher than calculated for the sea water in equilibrium with air containing 0.09 to 0.14 ppm of CO. The lowest ratio of measured CO concentration to be calculated, during a 24-hour period, was 5. Therefore, the net transfer of CO across the air–sea interface should be from water to the atmosphere. Supersaturation of water with CO was highest during daylight hours, and also higher in the area of the heavier marine vegetation. This could suggest biological production or photochemical decomposition of organic matter as possible sources of CO in water. If the average concentration of CO in the surface waters of the world ocean is approximately 10^{-5} ml/l, and if it is assumed that the upper 2 m of water could release the major portion of its CO to the atmosphere in 24 hours, then in 1 year the ocean could contribute approximately 9×10^{12} g of CO to the atmosphere, which is about 5% ofthe amount generated by burning fuels by man.

As to physiological effects of CO on human subjects, so far the only known physiological result of CO is binding with the new iron or porphyrin ring. Of the many hemoproteins in the human body, only hemoglobin is known to bind with CO to a significant degree at the low partial pressures, that people would be likely to be exposed to. The formation of carboxyhemoglobin (COHb) will impair tissue oxygenation by reducing Hb concentration and by eliminating low concentrating binding sites from Hb, which will make the release of O_2 from O_2Hb to tissues more difficult. The background concentration of COHb in human blood is of the order of 0.4%. With the increase of pCO in the breathing air COHb concentration will rise steadily until the equilibrium is reached—in approximately 12 hours. Exposure to 30 ppm of CO for 8 hours will produce an increase in COHb of 5%. Exposures for 5 hours to 10 to 12 ppm of CO have been shown to increase the COHb levels in nonsmokers by approximately 0.5%. Community air pollution with CO ranged from 5 to 60 ppm and in certain occupational areas may even be higher. Epidemiological studies on persons occupationally exposed to CO have failed to confirm the existence of the "chronic carbon monoxide intoxication"—a syndrome that was clinically poorly defined to begin with. There is ample evidence, however, that exposures to CO concentrations as low as 10 to 12 ppm for prolonged periods of

time add appreciably to the body burden of COHb. This would be particularly true of people with already impaired tissue oxygenation due to the lung diseases, poor blood circulation, anemia, etc. The available evidence suggests that daily average CO levels in excess of about 10 ppm may be associated with increased mortality of hospitalized patients with myocardial infarction. Exposures to CO that produce COHb concentrations of only 2% to 4% have been shown to affect certain sensory thresholds: ability to judge short intervals of time, brightness discrimination. In the opinion of the reviewer more attention should be given to the possibility of a mechanism other than COHb related hypoxia in dealing with the effects of CO on the central nervous system; particularly in view of the linear relationship between CO concentration in air and number of errors in judging time intervals, while the time of exposure was long enough only to produce COHb levels of less than 2%.

Finally, there is some evidence of adaptive changes upon prolonged exposure to CO as evidenced by increased red cell mass or Hb concentration. These changes require further studies and clarification, as indeed does almost every aspect of CO exposure mentioned here, with the possible exception of COHb formation which is well established and fairly well predictable as a function of CO. Cigarette smokers are a group of particular interest for researchers in this field, both in respect to adverse health effects and in respect to possible adaptive changes. The air inhaled with the cigarette smoke contains 400 ppm of CO and the average COHb concentration of a cigarette smoker is above 5%. There is enough evidence to suggest that even the relatively low concentrations of CO in the air may affect both the health and performance of the population and that biochemical, clinical, and epidemiological studies are not only warranted, but urgently needed.

The report contains a short review of the methods available for CO determination, and a method of calculating venous pO_2 as a function of COHb concentration. Detailed summary of tentative conclusions and recommendations for further research are included.

Pryor, A. J., Johnson, D. E., Jackson, N. N. (Southwest Research Institute, San Antonio, Texas) "Hazards of Smoke and Toxic Gases Produced in Urban Fires," *Final Report to Office of Civil Defense under Contract DAHC20-70-C-0212* (September 1969)

Section: K
Subjects: Life hazards; Smoke; Synergisms; Toxic gases; Urban fires

Authors' Abstract

In previous studies, the significance of synergistic action brought about by animal exposures to combinations of elements found within the combustion products in a mass fire environment was identified. An experimental program was undertaken to further define the life hazard in a mass fire environment resulting from exposures to these combustion products. Studies included exposures to combinations including the variables of carbon monoxide, temperature, oxygen, carbon dioxide, sulfur

dioxide, nitrogen dioxide, hydrogen cyanide, the presence of smoke (particulate matter), and all of the trace constituents to be found. The data from these tests and the results of the histopathological studies were reviewed in an effort to define the significance of human exposure to combustion products as found within the mass fire environment.

L. Operations Research, Mathematical Methods, and Statistics

Chambers, E. D. (Joint Fire Research Organization, Borehamwood, England) "An Experiment in Estimating Fire Losses," *Joint Fire Research Organization Fire Research Note No. 782* (September 1969)

Section: L
Subjects: Brigade; Correlation; Distribution; Fire loss

Author's Summary

Parameters of a fire loss distribution are estimated from a sample of fire reports. They do not contain any financial information.

Chandler, S. E. (Joint Fire Research Organization, Borehamwood, England) "Preliminary Analysis of Fire Reports from Fire Brigades in the United Kingdom, 1968," *Joint Fire Research Organization Fire Research Note No. 758* (March 1969)

Section: L
Subjects: Analysis; Fire brigades; Fire reports, 1968; Statistics; United Kingdom

Author's Introduction

A preliminary analysis of reports shows that, during 1968, local authority fire brigades attended 186,571 fires in England and Wales, 22,979 in Scotland, and 3,685 in Northern Ireland. The number of incidents attended by each brigade is given in Table 1.

Four firemen were killed at the scenes of fires. In England and Wales 327 members of the fire service were injured at fires; the corresponding figures for Scotland and Northern Ireland were 26 and 14, respectively.

Fire brigades assisted in the rescue of 789 persons from hazardous situations at fires in England and Wales; the corresponding figures for Scotland and Northern Ireland were 205 and 94, respectively. Six hundred and five people in England and Wales escaped by emergency means from fires; there were 41 such escapes in Scotland and 33 in Northern Ireland. Further details of casualties, rescues and escapes are given in Tables 2, 3, and 4.

There were 11 incidents in which mass evacuation of premises or a mass rescue was either necessary or advisable. These incidents involved two hospitals, two hotels, a school evening class, three buses, a railway train, a football ground and a departmental store. All the incidents except the departmental store, which was in Northern Ireland, were in England and Wales. There was an attendance of 34,000 at the football ground and the ground was evacuated; in the remaining incidents, the number of persons at risk was not generally known.

The analysis is based on reports received up to 7th March, 1969 and the figures are subject to revision when outstanding reports are received.

Chandler, S. E. (Joint Fire Research Organization, Borehamwood, England) "Fire Deaths in the Second Quarter of 1969," *Joint Fire Research Organization Fire Research Note No. 779* (September 1969)

Sections: L, K
Subjects: Fatalities; Fire statistics, 1969; United Kingdom

Author's Summary

A preliminary survey shows that 151 persons died in fires in the second quarter of 1969. One hundred and thirty-five of these were in England and Wales and 16 in Scotland. There were no fatal casualties in Northern Ireland. This is lower than the total for the first quarter of the year.

Two fires involving oil heaters each led to the deaths of four children in Birmingham. A fire in Durham, caused by children playing, gave rise to five deaths.

Gerrie, D. K. (Forest Research Institute, Department of Fisheries and Forestry, Ottawa, Candada) "Areal Representativeness of a Single Station's Drought Index," *Information Report FF-X-31* (December 1969)

Sections: L, J
Subjects: Drought index; Fire season; Quebec

Author's Abstract

Data from a dense network of 30 raingauge stations in each of two 37 mile square areas of northwestern Quebec are used to test how well drought indexes calculated from single raingauge stations located in the centre and in the corners of areas, represent the average areal drought index.

Data for 3 fire seasons in 1961, 1962 and 1963 indicate little difference from station to station; however, the central stations in each area proved to be slightly

superior indicators of the areal drought index, being more consistent from year to year and less prone to occasional large deviations from the areal drought index.

The central station in the North Area was representative of the areal drought index (within ±2 units of the Drought Index) on 91% of the observed days, and in the South Area on 87% of the observed days.

Kiil, A. D. and Quintillio, D. (Forest Research Laboratory, Calgary, Alberta, Canada) "Occurrence and Behavior of Forest Fires Related to Fire Danger Rating in Alberta, 1957–1963," *Forest Research Laboratory, Calgary, Alberta, Information Report A-X-25*

Sections: L, J, D
Subjects: Alberta; Danger rating; Forest fire; Statistics, 1957–1963

Authors' Abstract

This study, based on over 3,000 fire and weather reports, evaluates the Alberta and Alberta East Slope fire danger tables, and compares the various administrative units of the province in actual fire experience. Results indicate that fire business (rate of fire occurrence, rate of spread, area burned and length of fireguard build or held) increases with increasing danger class. The danger index appears to be equally effective in differentiating between fire conditions for both man-caused and lightning-caused fires.

Martin, S. B., Ramstad, R. W., Goodale, T., and Start, C. A. (URS Research Company, Burlingame, California) "Effects of Air Blast on Urban Fire Response," *Final Report to Office of Civil Defense under Contract NO0238-68-3011* (May 1969)

Section: L
Subjects: Air blast; Fire Analysis; Fire Blast; Fire response; Interaction; Nuclear-caused fires; Urban fires

Authors' Abstract

The objective of this research effort is to determine the nature and magnitude of the effects of blast-fire interaction on the vulnerability of urban areas to nuclear-weapon-caused fires.

The scope of the research is as follows:

1. Determination of the effects of the passage of the blast wave from a given nuclear weapon on the ignitions and fires started in various classes of structures and occupancies by the thermal pulse from the same weapon.

2. Determination of the effects of the structural alterations and fuel redistribution produced by the blast wave from a given weapon on the spread of the fires produced by that weapon in various use-class areas.
3. Performance of analyses of fire occurrence and behavior in specific, typical urban configurations for a variety of blast-loading and thermal-loading conditions.
4. Assessment of the probable magnitude of the influence of blast-fire interaction on urban fire vulnerability in the urban areas considered.

Principal emphasis is being given to the effects of detonations of strategic-yield weapons for distances from ground zero at which operationally significant levels of damage to representative urban targets would occur.

This report summarizes the results of research accomplished during the initial contract in the subject area described above.

Ramachandran, G. and Kirsop, Patricia (Joint Fire Research Organization, Borehamwood, England) "Preliminary Analysis of Large Fires during 1968," *Joint Fire Research Organization Fire Research Note No. 763* (May 1969)

Section: L
Subjects: Large fires; Loss; Statistics, 1968; United Kingdom

Authors' Summary

This note contains a preliminary analysis of large fires during 1968. These are fires which cost £10,000 or more in direct damage. There were 1005 such fires during 1968 resulting in a total loss of £61.6 million. Of these 38 were in outdoor hazards some of which spread to buildings. The average loss per large fire, in static money terms decreased during the seven year period 1962 to 1968 although the total loss in static terms and the average loss at current values both increased.

M. Model Studies and Scaling and Laws

Takata, A. N. (IIT Research Institute, Chicago, Illinois) "Power Density Rating for Fire in Urban Areas," *Final Technical Report to Office of Civil Defense under Contract NO0228-68-C-2687* (April 1969)

Sections: M, L, I, J
Subjects: Heat release rate; Power density rating; Urban fires

Author's Abstract

This study involves the development of a computer code to predict the power density (rate of heat generation) from fires in typical built-up areas of San Jose and

Albuquerque as a result of a nuclear burst. A scheme was also developed to rapidly estimate the power density by hand calculation. In addition to predicting the power density, the code predicts the radiant intensities in the streets from the burning buildings and the radiant heating of the air. Studies were conducted to ascertain the effects of the thermal environment on personnel in the streets and related to the effects of fallout. Safe travel or exposure times are indicated for the two effects.

N. Instrumentation and Fire Equipment

Bergen, J. D. (Rocky Mountain Forest and Range Experiment Station, U. S. Forest Service, Fort Collins, Colorado) "Heated Thermopile Anemometer Compared with Sensitive Cup Anemometer in Natural Air Flow," *U.S. Forest Service Research Note* RM-147 (1969)

Sections: N, J
Subjects: Power density; Meteorology; Thermopile anemometer; Wind

Author's Abstract

Comparison of twenty 5-minute average speeds showed discrepancies of as much as ±50 percent with windspeeds ranging from 2.8 to 6.6 miles per hour. The magnitude and sense of the deviations did not vary systematically with turbulence intensity of speed. Measurements were made at an air temperature of about 20°C.

Kumano, Y. (Fire Research Institute of Japan, Tokyo, Japan) "High Speed Flash Photography of Hose Streams," *Report of Fire Research Institute of Japan* 4 (4), 86–96 (December 1953)

Sections: N, I
Subjects: Flash photography; Hose streams; Hydraulics

Author's Conclusions

Descriptions were made in this report of the application of high-speed flash photography in the study of a fire stream behavior. Although the resulting photographs obtained so far have fallen short of the author's primary objective to get a clear view of the dependence of the stream-disintegration characteristics on the nozzle size and nozzle pressure, the well-defined image of every portion of the stream stopped will provide unprecedented means for clearer understanding of the general feature of the "solid" hose stream, and, in that very sense, they will be of no little significance to those interested in the hydraulic problems in fire protection.

As for the flash-photographic unit proper employed in this experiment, it worked quite well. The possible combination of this unit with an ultra high-speed shutter, such as the Kerr cell shutter, will do away with the difficulties due to the "nighter" experiment and will find far more extended uses in various fields of fire protection engineering.

O. Miscellaneous

Butler, C. P. (Naval Radiological Defense Laboratory, San Francisco, California) "Operation Flambeau—Civil Defense Experiment and Support," *Final Report under Contract No. DAHC20-67-C-0149, OCD Work Unit No. 2561B for the Office of Civil Defense* (May 1969)

Sections: O, D
Subjects: Civil Defense; Flambeau Fire; Mass fires

Reviewed by A. A. Brown

This document is a portion of the final report on a study of mass fires. The study, sponsored by the Office of Civil Defense is known as "Operation Flambeau." It has been a continuing study, beginning in 1962 with detailed instrumentation of the behavior of fire in a single array of fuels, consisting of approximately 20 tons of pinyon and juniper trees arranged in a 50 ft sq area to a depth of 6 ft, then progressing through successively larger fires, fed by an increasing number of such arrays, and culminating in this fire designated Flambeau 760–12, which involved 342 such piles of fuel in rectangular patterns simulating fuel loading along city streets, and covering 44 acres. It was ignited on September 29, 1967.

Experimental data consist of measurements giving a detailed time history of temperature and air movement, including development of the convection column, coupled with simultaneous observations of the fire's behavior. This report is confined to the observations.

These observations are of particular interest on two counts: (1) the first is as cited by the editor, C. P. Butler, "Visual impressions of the magnitude of a large fire are the sole method by which officials may make immediate decisions on its severity. Past impressions from eyewitnesses lack instrumental verification of physical parameters defining the magnitude or severity inside the fire zone. Flambeau Fire 760–12 offered an opportunity for witnesses to describe their impressions of an instrumented fire." (2) The second is the live reporting by the team of seven observers, each a scientist and a qualified expert in fire research with previous familiarity with big fires but with a somewhat different background and approach to the problem of identifying and reporting significant phenomena. These seven were stationed around the area and each carried on independent observations at a different location during the early part of the burn. Their verbal reports in the form of tape recordings are the primary reference for which the report provides a brief summary. These observers and their sponsoring agency are as follows.

1, 2, and 3: Theodore G. Storey, Research Forester; Clive M. Countryman, Project Leader; Thomas Y. Palmer, Project Leader (Pacific Southwest Forest and Range Experiment Station, Riverside, California).
4: Richard C. Rothermel, Project Leader (Intermountain Forest and Range Experiment Station, Missoula, Montana).
5: Michael Woolliscroft (Fire Research Station, Borehamwood, England).
6: A. M. Western (Home Office, Horseferry House, Dean Ryle Street, S.W.1, England).
7: Abraham Broido (Pacific Southwest Forest and Range Experiment Station, Berkeley, California).

Rather than quote individual observers or the editor directly it appears useful to undertake a brief composite summary of their account of the fire on a time history basis starting with the time of ignition as zero, which was at 7:57 a.m., September 29, 1967. Proceeding in this fashion, the picture they give of the behavior of the fire is about as follows:

0 minute. Winds from the S–SW very light, 1–2 miles per hour perhaps up to 6 miles aloft. Simultaneous ignition of piles of fuel by igniters was highly successful. In a few seconds fire was visible at two or more points in all piles observed.

+1 min. Smoke now thick, flames to 10 ft in length and growing. Smoke drifting to NE and beginning to form convection column 75–80 ft high on downwind side of area to the NE.

+2 min. Convective activity building fast, flames all leaning in along south side of fire. Two convection columns developing, near the ground, one near the center of test area and one over NE corner merging above to form the main column which is rising rapidly. It is tilted about 60° to the NE for about the length of the fire area, then heads straight up. Flames 30 ft near center of test area but up to 50 ft at NE, downwind. Indrafts overcoming the prevailing wind near the ground. Flames turbulent, beginning to pulsate and first background sound effects noticeable.

+3 min. Convection column is still building, and prevailing wind increasing somewhat. Looking down the streets between rows of piles, flames are now reaching across them. In the southwest corner a horizontal fire whirl looking like a barrel was seen rolling into the fire. In the northeast corner, flame and smoke pulled in toward the center so strongly that it appeared to be flowing on the ground and a fire whirl about six plots in, began. It was violent, but short-lived.

+4 min. Convection cap now visible on top of the convection column almost directly overhead. Another fire whirl forming in the NE corner at 3 min and 39 sec followed by two fire whirls near the north edge of the test area extending 50 to 80 ft into the convection column. It is now starting to pinch in at about 100 ft above ground and is rising higher before bending off toward the northeast. Turbulence still increasing.

+5 min. Fire now approaching peak intensity with almost continuous fire whirl activity in the northeast quadrant. First one large fire whirl was observed on the east side with strong indrafts pulling into it. Then a second and a third formed. As they dissipated a more powerful one formed in the east edge which lasted 15 to 20 sec and carried flames 200 to 300 ft into the air. As it slowed down, another formed north of it, but it built back to new violence with embers swirling around for a 50 to 75 ft radius around it. It was turning counterclockwise and seemed to be pulling out of two plots though centered on one. One fire whirl moved out of the test area into the sage brush and set a number of spot fires that had to be controlled by the fire crew. Roar from fire continuous.

+7 min. White condensation cap forming over the top of the convection column. One fire whirl turning counterclockwise in the northeast seems to have been continuous. Another further in the northeast corner is turning clockwise. Indraft now very strong.

+8 to 11 min. Continuing fire whirls, some very violent. Distant booming or roaring sound almost continuous. A powerful whirl on north central edge of test area has an orange color, makes a violent whistling noise, and is carrying green brush and large sticks up to 50 ft into the air and dropping them outside the test area. Smoke column getting lighter in color, flame heights 20 to 30 ft now but burning is still intense.

11 to 15 min. Wind has picked up to about 15 miles per hour or more. More violent smoke whirls which pick up debris but drop it as soon as they move away from their heat source. White condensation cap on top of convection column becoming very large almost directly overhead.

+17 to 21 min. Fire activity decreasing, can see down the aisles about 300 ft, flame no longer reaches across. Can approach to within 40 ft of fire. Fine fuels have burned, heavier fuels now burning at slower rate. But fire whirls continue to generate. Have set two fires outside test area, one at 100 ft, another at 200 ft, but smoke from them is sucked back into fire against prevailing wind.

+27 min. Fire whirl blew all radiation instruments off their mountings near north edge of area.

+33 min. Spotfires from whirls set by piece of bark 2 by 3 in. and by stick 3 ft long and about 2 in. in diameter 240 ft from fire.

+1 hour and more. Fire whirls at lower intensities continued to form for over an hour after ignition. Observers agreed that the main whirl in the northeast corner never really stopped during the course of the fire, it was matched by another whirl located farther in and rotating in the opposite direction. These whirls did not seem to be a random event but were triggered by interaction between indraft and prevailing winds on the downwind border. Observers also agreed that fire intensities differed significantly between the upside and downwind portions of the 44 acre test area. At the upwind end green vegetation remained green between burning piles while at the downwind end everything was seared not only between piles but for some distance outside the area.

Quantitative conclusions must await analysis of the detailed measurements obtained through instrumenting this fire.

However, the eyewitness information serves the very important purpose of improving understanding of mass fire behavior and the nature of its threat to humans.

TRANSLATIONS

Khaiken, B. I., Filonenko, A. D., and Kuhdyaev, S. I. "Flame Propagation When Two Successive Reactions Take Place in a Gas," *Physics of Combustion and Explosion* 4 (4), 591–599 (1968) In Russian.

Sections: G, H, I
Subjects: Flame propagation; Flame theory; Successive reactions

Translated by L. Holtschlag*

According to modern ideas the burning of condensed explosives is a complex multistage process with chemical reactions taking place in various phases.[1–3] The multi-stage nature of the process can be divided conventionally into a physical side and a chemical side.

The physical stages are contingent on the existence of a number of zones with various physical properties (fixed; foamy; with condensed particles moving in the gas; gaseous). Chemical reactions take place in each of these zones. The formation of zones is connected with the various physical and chemical processes that take place during burning, e.g., dispersion, evaporation, etc.[4–10]

The chemical stages are connected with the complexity of the chemical processes, with the possibility that chain, successive, and parallel reactions take place during combustion. There exists a number of papers in which an examination is made of flame propagation in systems with a complicated chemistry.[11–14,15] These papers are devoted chiefly to calculation of the flame propagation rate in a gas during chain reactions.

One of the possible forms of complex chemical reactions in a flame may be successive reactions: in such reactions the main task is to find criteria which will permit determination of the chemical reaction which governs the combustion process, i.e., which is the leading reaction. It is also necessary to investigate the influence exerted by interaction of the chemical stages on the burning rate. These questions are examined in the present paper for the case when two successive exothermal reactions take place in the gas:

$$A_1 \xrightarrow{k_1(T)} A_2 \xrightarrow{k_2(T)} A_3.$$

Note that examination of multi-stage chemical reactions in a gas can be applied to the combustion of condensed explosives if the combustion rate of the explosives is governed by the gas zone (in conformity with the theory of Belyaev–Zel'dovich.[1,16]

It is expedient to explain the distinctive features of flame propagation in a system with successive reactions by formulating the problem in a simple manner. We shall therefore assume that all the coefficients of binary diffusion are the same and are equal to the coefficient of thermal conductivity, i.e., $D=\lambda/\rho_c$ (λ is the coefficient of

* Applied Physics Laboratory, The Johns Hopkins University. Translation 2277, May 1969. By permission.

thermal conductivity; ρ is density, c specific heat, D the coefficient of diffusion); the components of the mixture have essentially equal heat capacities and molecular weights. Under these assumptions the system of equations describing the process of stationary flame propagation has the form

$$D(d^2a_1/dx^2) - u(da_1/dx) - \Phi_1(a_1, T) = 0,$$

$$D(d^2a_2/dx^2) - u(da_2/dx) + \Phi_1(a_1, T) - \Phi_2(a_2, T) = 0,$$

$$D(d^2T/\partial x^2) - u(dT/\partial x) + (Q_1/c)\Phi_1(a_1, T) + (Q_2/c)\Phi_2(a_2, T) = 0, \quad (1)$$

with boundary conditions

$$x \to -\infty, \quad T = T_0, \quad a_1 = 1, \quad a_2 = 0;$$

$$x \to +\infty, \quad dT/dx = 0, \quad a_1 = 0, \quad a_2 = 0.$$

The notation is as follows: $\Phi_1(a_1, T)$, $\Phi_2(a_2, T)$ are the rates of the chemical reactions $A_1 \to A_2$, $A_2 \to A_3$ respectively;

$$\Phi_1(a_1, T) = k_1(T)a_1^{n_1}k_{10}\rho^{n_1-1}a_1^{n_1} \exp(-E_1/RT);$$

$$\Phi_2(a_2, T) = k_2(T)a_2^{n_2} = k_{20}\rho^{n_2-1}a_2^{n_2} \exp(-E_2/RT);$$

x is a coordinate; a_1, a_2 are the relative concentrations of the substances A_1, A_2; T is temperature; T_0 initial temperature; Q_1, Q_2 thermal effects of the first and second reactions per unit mass of starting material; E_1, E_2 are the activation energies of the first and second reactions; n_1, n_2 are the orders of the reactions; k_{10}, k_{20} are pre-exponential factors; u is the desired flame propagation rate. The relative concentrations of the substances A_1, A_2, A_3 are interrelated by the formula $a_1 + a_2 + a_3 = 1$. This is why system (1) contains no equations for a_3.

Analysis of the results of numerical solution of system of Eq. (1) can be simplified to an appreciable extent if the following combustion temperatures and single-stage flame propagation rates are first introduced: $T_1 = T_0 + Q_1/c$ is the combustion temperature that would exist if there were no second reaction; $T_2 = T_0 = Q_1/c + Q_2/c$ is the combustion temperature corresponding to completion of the two reactions; $u_1(T_2)$ is the rate that corresponds to the case when no second reaction takes place, while the first reaction takes place with a total heat effect (combustion temperature T_2); $u_1(T_1)$ is the propagation rate which would exist if only the first reaction would take place, while there is no second reaction at all (combustion temperature T_1); $u_2(T_2)$ is the propagation rate corresponding to the case when only the second reaction takes plase with its own thermal effect (combustion temperature T_2).

According to the formula proposed by Ya. B. Zel'dovich and D. A. Frank-Kamenetskii[17] these rates have the form

$$u_1(T_2) = (2Dk_{10}n_1!\rho^{n_1-1})^{1/2}[cRT_2^2/(Q_1+Q_2)E_1]^{(n_1+1)/2} \exp(-E_1/2RT_2),$$

$$(Q_1+Q_2)E_1/cRT_2^2 \gg 1, \quad E_1/RT_2 \gg 1;$$

$$u_1(T_1) = (2Dk_{10}n_1!\rho^{n_1-1})^{1/2}(cRT_1^2/Q_1E_1)^{(n_1+1)/2} \exp(-E_1/2RT_1),$$

$$Q_1E_1/cRT_1^2 \gg 1, \quad E_1/RT_1 \gg 1;$$

$$u_2(T_2) = (2Dk_{20}n_2!\rho^{n_2-1})^{1/2}(cRT_2^2/Q_2E_2)^{(n_2+1)/2} \exp(-E_2/2RT_2),$$

$$Q_2E_2/cRT_2^2 \gg 1, \quad E_2/RT_2 \gg 1.$$

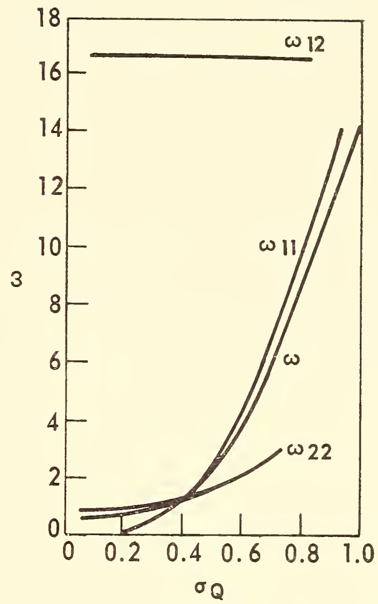

Fig. 1. Function $\omega(\sigma_Q)$; $\theta_0 = 10$, $\beta = 0.09$, $\sigma_E = 0.3$, $\sigma_k = 0.5$.

The inequalities indicate the range in which the formulas can be applied. As is well known, these formulas are applicable at high activation energies and thermal effects. As is shown in Refs. 18 and 19, however, the range of applicability of the Zel'dovich–Frank-Kamenetskii formula does not require these inequalities to be strongly fulfilled, because of the error compensation that occurs in the expansion of the exponent and because of the neglect of the convective term.

An investigation of system (1) shows that the equation for a_2 can be omitted, since the following relationship exists between the temperature and the concentrations:

$$a_1[(Q_1+Q_2)/c]+a_2(Q_2/c)+T=[(Q_1+Q_2)/c]+T_0.$$

Then system (1) for first-order reactions ($n_1=n_2=1$) has, in dimensionless variables, the form

$$(d^2a_1/d\xi^2)-\omega(da_1/d\xi)-\sigma_k a_1 \exp\left(\frac{1-\sigma_E}{\beta}-\frac{\sigma_E\theta}{1-\beta}\right)=0,$$

$$(d^2\theta/d\xi^2)-\omega(d\theta/d\xi)-\theta_0\left\{\sigma_k\sigma_Q a_1 \exp\left(\frac{1-\sigma_E}{\beta}-\frac{\sigma_E\theta}{1-\beta}\right)+\frac{(1-\sigma_k)(\theta-\theta_0 a_1)}{\theta_0}\right.$$
$$\left.\times \exp\left[\frac{\sigma_E}{\beta}-\frac{(1-\sigma_E)\theta}{1-\beta\theta}\right]\right\}=0 \quad (2)$$

with boundary conditions

$$\xi\to-\infty,\qquad \theta=\theta_0,\qquad a_1=1;$$
$$\xi\to+\infty,\qquad \theta=0,\qquad a_1=0,$$

where $\xi = x[(k_{10}+k_{20})/D]^{1/2} \exp[-(E_1+E_2)/2RT_2]$ is a dimensionless coordinate, $\theta = (\{T_0 - T + [(Q_1+Q_2)/c]\}(E_1+E_2)/RT_2^2)$ is the dimensionless temperature, and $\omega = u\{D(k_{10}+k_{20})^{-0.5} \exp[(E_1+E_2)/2RT_2]\}$ is the dimensionless burning rate.

The parameters are

$$\theta_0 = [(E_1+E_2)(Q_1+Q_2)]/cRT_2^2, \quad \beta = RT_2/(E_1+E_2),$$

$$\sigma_k = k_{10}/(k_{10}+k_{20}); \quad \sigma_Q = Q_1/(Q_1+Q_2), \quad \sigma_E = E_1/(E_1+E_2).$$

The parameters σ_k, σ_Q, σ_E are the ratios of the pre-exponent, the heat effect and the activation energy of the first reaction to the sum of the corresponding quantities. Two parameters θ_0, β depend on the initial temperature. Only the parameter σ_k depends on the pressure if one of the reactions is monomolecular and the other bimolecular.

The dimensionless burning rates, denoted by ω_{12}, ω_{11}, ω_{22} will correspond to the previously introduced rates $u_1(T_2)$, $u_1(T_1)$, $u_2(T_2)$. The first subscript of the dimensionless rates indicates the kinetics of the reaction that governs the burning rate; the second subscript indicates the combustion temperature. These rates and their range of application are given according to Zel'dovich and Frank-Kamenetskii:

$$\omega_{12} = \{(2\sigma_k)^{1/2} \exp[(1-\sigma_E)/2\beta]\}/\theta_0\sigma_E,$$

$$\theta_0\sigma_E \gg 1, \qquad \sigma_E/\beta \gg 1; \tag{3}$$

$$\omega_{11} = \frac{(2\sigma_k)^{1/2}(1+\theta_0\beta\sigma_Q-\theta_0\beta)^2 \exp\left[\dfrac{1+\theta_0\beta\sigma_Q-\theta_0\beta-\sigma_E}{2\beta(1+\theta_0\beta\sigma_Q-\theta_0\beta)}\right]}{\theta_0\sigma_Q\sigma_E},$$

$$\theta\sigma_Q\sigma_E/(1+\theta_0\beta\sigma_Q-\theta_0\beta)^2 \gg 1, \qquad \sigma_E/\beta(1+\theta_0\beta\sigma_Q-\theta_0\beta) \gg 1; \tag{4}$$

$$\omega_{22} = \{[2(1-\sigma_k)]^{1/2} \exp(\sigma_E/2\beta)\}/[\theta_0(1-\sigma_Q)(1-\sigma_E)],$$

$$\theta_0(1-\sigma_Q)(1-\sigma_E) \gg 1, \qquad (1-\sigma_E)/\beta \gg 1. \tag{5}$$

System (2) was solved on a computer. Studied at the same time were the functions $\omega(\sigma_Q)$, $\omega(\sigma_E)$, $\omega(\sigma_k)$ and $\omega(\beta, \theta_0)$ in a broad range of parameters: $0<\sigma_Q<1$, $0<\sigma_E<1$, $0<\sigma_k<1$, $0.08 \leq \beta \leq 0.107$, $12 \geq \theta_0 \geq 6.8$.

The results of calculating the dependence of the burning rate on the initial temperature $\omega(\beta, \theta_0)$ were processed in the coordinates $(\ln\omega - \frac{1}{2}\beta)$ and β for a clear presentation of the dimensionless temperature coefficient of the burning rate $\alpha = d \ln\omega - \frac{1}{2}\beta)/(d\beta)$. The dimensional $(\alpha_p = d \ln u/dT_0)$ and dimensionless burning rate coefficients are related by

$$\alpha = \alpha_p[(E_1+E_2)/R],$$

Also determined along with the burning rate was the structure of the flame front (temperature profile θ; concentration profile a_1, a_2; and the functions of the heat release rate $f = d^2\theta/d\xi^2 - \omega\, d\theta/d\xi$).

The method of numerical solution of the problem is outlined in Ref. 20. Let us note here only that in the majority of cases the corresponding nonstationary problem was solved until we established this method. When this method proved to be only poorly applicable (slow convergence and need for large computer memories), we made direct use of a simple method of approximate solution of the stationary problem.

Shown in Figs. 1, 2, 3 are some results of calculating the flame propagation rate; they were obtained while varying the parameters σ_Q, σ_E, σ_k. Plotted in these same figures are the values ω_{12}, ω_{11}, ω_{22}, as obtained from the approximate formulas (3), (4), (5). From the figure it is evident that the burning rate ω is close to any of the rates introduced above, ω_{12}, ω_{11}, ω_{22}, for any values of the parameters. Some deviations occur where the approximate formulas of Zel'dovich are poorly applicable. Even in these cases, however, the error in the absolute value of the rate is not very large. But if the single-stage rates satisfy the conditions under which Zel'dovich's formulas are applicable in the transition region, transition from one regime to the other takes place within a narrow range of parameters.

It is important to note that in all cases there exist characteristic points at which transition from one regime to the other occurs. Such points are either points of inflection (see Fig. 1) or extrema points (maxima and minima) (see Figs. 2, 3). The presence of characteristic points and the insignificant differences in the values of the rate (especially if the rates ω_{12}, ω_{11}, ω_{22} are calculated not according to the approximate formulas of Zel'dovich, but exactly) permit us to state that the governing stage can always be established. The effect of stage interaction shows up mainly in the fact that when the parameter changes transition is possible from one regime to the other. Stage interaction does not lead to any other qualitative effects and exerts only an insignificant quantitative effect.

It should be noted that there is some disagreement as to the concept of the leading stage. If the second reaction is the leading one in the regime with $\omega=\omega_{22}$, then, e.g., regimes with $\omega=\omega_{12}$ and $\omega=\omega_{11}$ differ, but the kinetics of the second stage govern the burning process in both cases; i.e., the first reaction is governing. In calling a stage

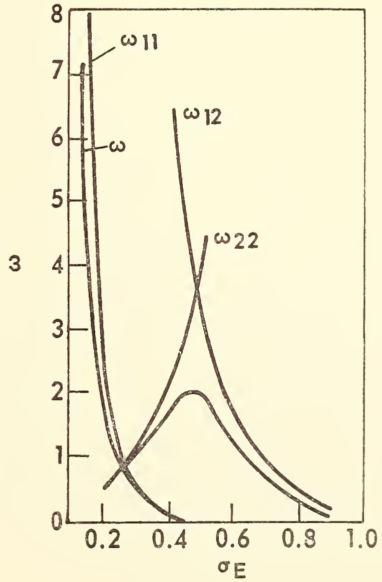

Fig. 2. Function $\omega(\sigma_E)$; $\theta_0 = 10$, $\beta = 0.09$, $\sigma_Q = 0.3$, $\sigma_k = 0.5$.

the governing stage, therefore, it is also necessary to define the thermal effect with which it takes place (or at what temperatures). This fact is also emphasized in Refs. 6 and 7.

It is interesting that the curve for the burning rate corresponds to the curve of ω_{12}, ω_{11}, or ω_{22} that lies between two values in the given range of parameters. Considering that ω_{12} is always greater than ω_{11} (since both rates are governed by the same kinetics, but the rate ω_{12} corresponds to the higher burning temperature), only three inequalities between the rates ω_{12}, ω_{11}, and ω_{22} can be written:

$$\omega_{12} > \omega_{11} > \omega_{22}, \tag{6}$$

$$\omega_{22} > \omega_{12} > \omega_{11}, \tag{7}$$

$$\omega_{12} > \omega_{22} > \omega_{11}. \tag{8}$$

The middle rate in each inequality coincides with the true burning rate. As is evident from the inequalities, the leading stage can be determined in the various cases as the fast (6) as well as slow (7), (8) chemical reaction. Thus, by computing the rates ω_{12}, ω_{11}, ω_{22} from the formula of Zel'dovich and Frank-Kamenetskii and intercomparing these rates, it is possible, according to what was said above, to obtain an idea of the magnitude of the burning rate and to establish which stage of the process is the leading stage.

According to (6), (7), (8) a change in combustion regime is accomplished if one inequality is replaced by another upon change of any parameter. From the graphic representations it is clear that this occurs if the curve of the dependence of ω_{22} on this parameter intersects any of the curves of ω_{12} or ω_{11}. The equalities $\omega_{11} = \omega_{22}$ and $\omega_{12} = \omega_{22}$ determine the conditions of transition from one regime to another. Direct

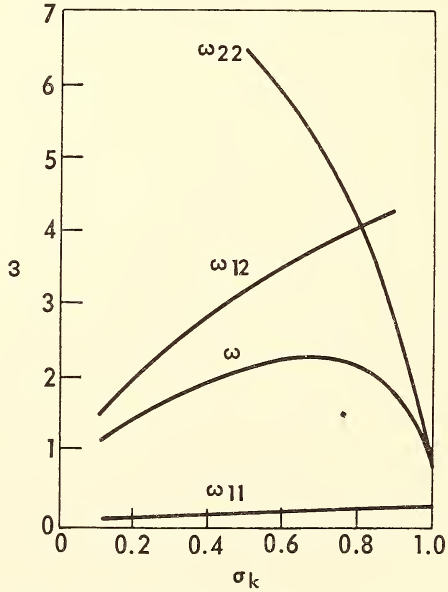

Fig. 3. Function $\omega(\sigma_k)$; $\theta_0 = 10$, $\beta = 0.09$, $\sigma_E = 0.5$, $\sigma_Q = 0.5$.

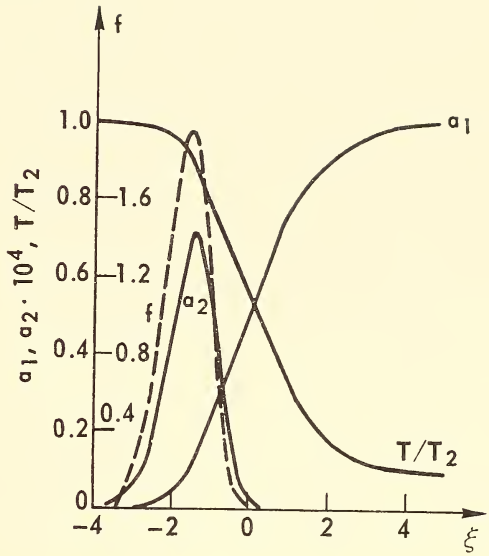

Fig. 4. Profiles of the temperature, concentration and heat-release rate at the flame front in the regime $\omega = \omega_{12}$; $\theta_0 = 10$, $\beta = 0.09$, $\sigma_E = 0.8$, $\sigma_Q = 0.3$, $\sigma_k = 0.5$, $\omega = 0.29$.

transition from the regime ω_{11} to ω_{12} and back again, bypassing the stage ω_{22}, is impossible, since the equality $\omega_{11} = \omega_{12}$ cannot be fulfilled.

In principle, the conditions of change of regime are met even in cases when other mechanisms govern the chemical reactions in each stage (e.g., higher-order reactions, chain reactions) upon appropriate change of the form of ω_{12}, ω_{11}, ω_{22}.

Let us now consider the structure of the flame front in the various regimes. Shown in Fig. 4 is the flame front structure in the regime with $\omega = \omega_{12}$. The characteristic features of this regime are as follows: a) there is one maximum heat-release rate; b) the concentration of intermediate product a_2 is very small. The smallness of the concentration a_2 is connected with the fact that the second reaction is faster than the first in the entire range of temperatures reached during combustion.

The two other regimes correspond to the case when the first reaction is fast. Shown in Fig. 5 is the structure of the flame front in the regime $\omega = \omega_{11}$. The characteristic features of this regime are: a) there are two maxima of the heat-release rate, separated in space, the maximum of the first stage being greater than that of the second. The second reaction takes place in the self-ignition regime[21–22] (the term $\omega(d\theta/d\xi)$ can be neglected in the heat conduction equation in the zone of the first reaction and the term $d^2\theta/d\xi^2$ in the second); b) there is a temperature plateau separating the two heat-release zones where the concentration of intermediate product a_2 is close to unity. In this regime the first reaction is fast and takes place with a sufficient thermal effect. When the distance between the two heat-release zones is sufficiently large, the heat-release zone of the second reaction may appear as a second flame. In a number of cases, when this distance is small, the temperature plateau is only weakly pronounced, reducing essentially to the presence of an inflection in the temperature profile (Fig. 6).

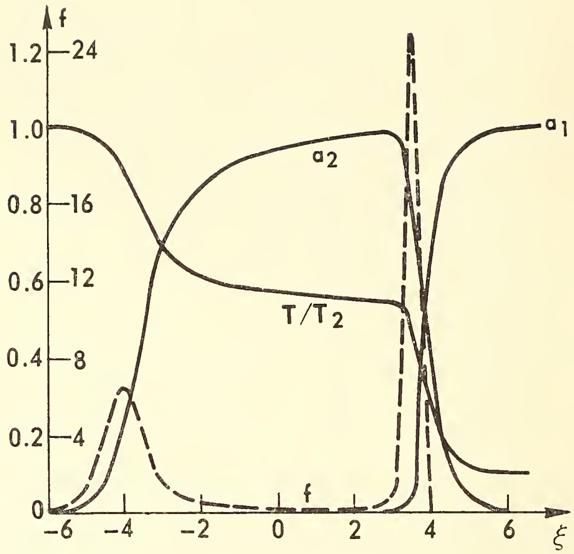

Fig. 5. Profiles of the temperature, concentration, and heat release rate at the flame front in the regime $\omega = \omega_{12}$; $\theta_0 = 0$, $\beta = 0.09$, $\sigma_E = 0.3$, $\sigma_Q = 0.5$, $\sigma_k = 0.5$, $\omega = 2.23$.

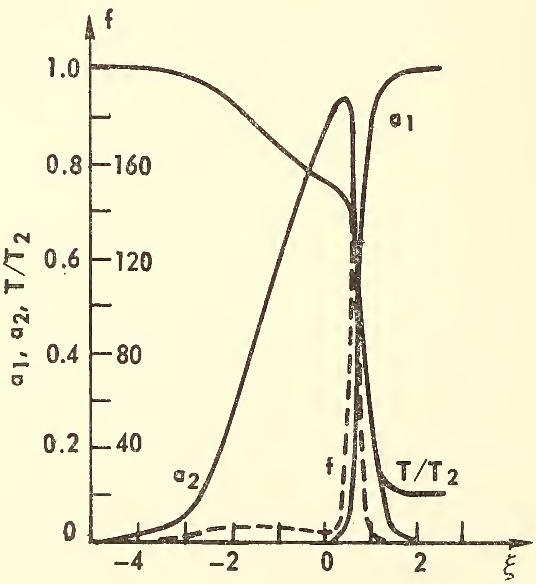

Fig. 6. Profiles of the temperature, concentration and heat-release rate in the flame front in the regime $\omega = \omega_{11}$; $\theta_0 = 10$, $\beta = 0.9$, $\sigma_E = 0.3$, $\sigma_Q = 0.7$, $\sigma_k = 0.5$, $\omega = 5.97$.

Shown in Fig. 7 is the structure of the flame front in the regime with $\omega=\omega_{22}$. Characteristic of this regime are: a) two maxima of the heat-release rate, separated in space, the maximum being greater in the second than in the first stage; b) in contrast with the preceding case a temperature plateau is absent. In this regime, as in the preceding, the first reaction is faster than the second, but takes place with an insufficient thermal effect. The burning rate is therefore determined by the kinetics of the second reaction, while the first is "controlled" by the thermal flux from the zone of the second reaction.

In the experimental investigation of specific substances the initial temperature and pressure are usually varied. When these quantities are varied within certain limits transition from one regime to the other is possible.

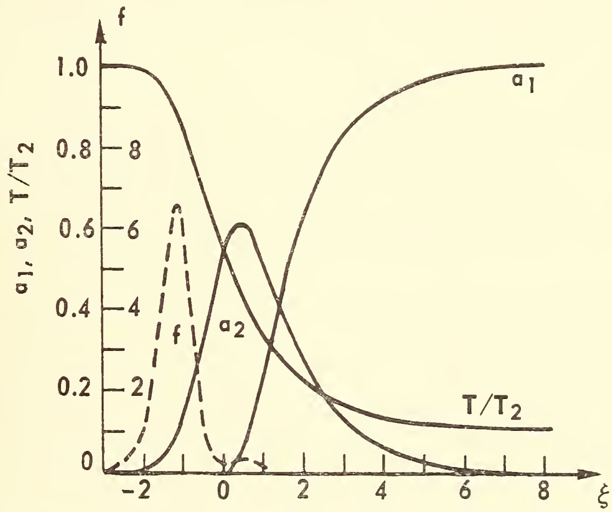

Fig. 7. Profiles of the temperature, concentration and heat-release rate in the flame front in the regime $\omega = \omega_{22}$; $\theta_0 = 10$, $\beta = 0.9$, $\sigma_E = 0.3$, $\sigma_Q = 0.05$, $\sigma_k = 0.5$, $\omega = 0.7$.

Shown in Fig. 8 is the transition of the leading stage from the high-temperature region ($\omega=\omega_{22}$) to the low-temperature region ($\omega=\omega_{11}$) with an increase in the initial temperature T_0. The angle formed by the curve with the axis of abscissae is proportional to the temperature coefficient of the burning rate. As is evident from the figure, when the initial temperature increases, the temperature coefficient increases abruptly, jumpwise. A similar phenomenon is observed during the burning of nitroglycerin N powder,[23] although according to Ref. 4 this is due to other reasons (transition of the leading stage from the gas zone to the condensed zone).

If the rates of the first and second reactions depend in different ways on the pressure, i.e., if one of the reactions is monomolecular and the other bimolecular, transition from one regime to another is also possible when the external pressure changes. At the same time, if the change of regimes takes place as a result of pressure increase, there will be an increase in the exponent of the pressure-dependence of the burning rate, $\nu (u \sim p^\nu)$.

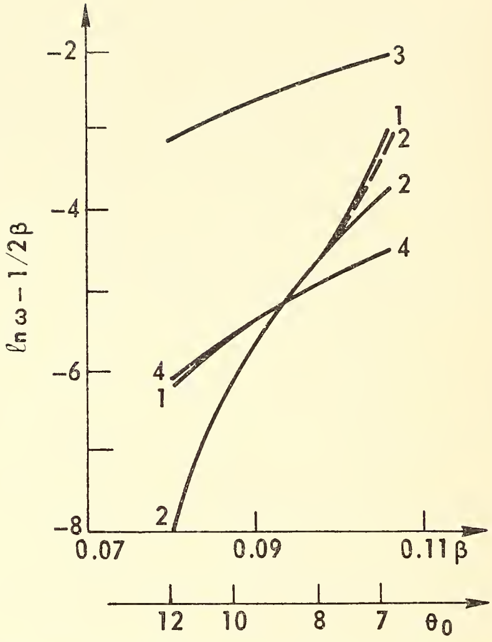

Fig. 8. The function $\omega(\beta,\theta_0)$; $\sigma_E = 0.3$, $\sigma_Q = 0.3$, $\sigma_k = 0.5$. 1—ω; 2—ω_{11}; 2′—exact value of ω_{11} obtained on a computer; 3—ω_{12}; 4—ω_{22}.

Also of interest is the pressure-dependence of the distance between the heat-release zone (Δx) (second reaction in the self-ignition regime). If the distance between zones is large,

$$\Delta x = ut \sim p^{(\frac{1}{2}n_1 - n_2)}, \tag{9}$$

where $t \sim p^{(-n_2+1)}$ is the induction period of an adiabatic thermal explosion,[24] $u = u_1(T_1) \sim p^{(\frac{1}{2}M_1 - 1)}$.

A regime with $\omega = \omega_{11}$ is realized when burning gas mixtures containing NO_2,[25] methyl nitrate,[26] and nitroglycol.[1,7,27] In a number of cases a second flame arises when burning these materials (sometimes such a flame does not even result from heat losses), and this flame has an appreciable effect on the burning rate. This indicates that the reaction in the second flame takes place in the self-ignition regime. According to the literature data, the multistage chemistry of these materials is associated with the fact that the final product of the first stage, NO, reduces in the second stage to N_2. These stages are, of course, considerably more complex than in the problem being considered. However, if the rates are not assigned specific values in the individual regimes, the basic conclusions are applicable to more complex reactions as well.

We note that during the study of nitroglycol it was found that the separation between the zones (the distance between the first and second flames) $\Delta x \sim p^{-1.65}$.[27] If in formula (9) we set $n_1 = 1$, $n_2 = 2$ (according to the data in the literature on the kinetics of these reactions[1,25], we find $\Delta x \sim p^{-1.5}$.

Some conclusions as to the effect of various additions on the burning rate can also be drawn from the problem being examined. In accordance with Ref. 8 let us consider the question of the influence of a small catalytic addition which only increases the rate of the first reaction without bringing about any change whatever in the combustion process. Let the leading stage before introducing the addition be the second stage. According to the preceding, $\omega_{12} > \omega_{22} > \omega_{11}$ in this case. If the catalytic addition does not raise the rate of the first reaction too strongly (the inequality is fulfilled), the burning rate does not change (in conformity with Ref. 8), since the catalytic addition does not influence the rate ω_{22}. If, however, owing to the catalytic addition, the rate of the first reaction has increased substantially (the inequality between ω_{11} and ω_{22} changed), transition to the regime with $\omega = \omega_{11}$ occurs. In this case the combustion pattern changes appreciably.

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MEETINGS

1st All-Union Symposium on Combustion and Explosion—Results of Meeting *Physics of Combustion and Explosion* 4, 443–445 (1968) In Russian, translated by L. Holtschlag.

Section: O
Subject: Symposium on combustion and explosion

Seven hundred and fifty people from 117 organizations participated in the work of the symposium, which was held from 19 to 24 February 1968 in the Noginsk Scientific Center of the Academy Sciences, U.S.S.R. Two hundred and eight reports were presented at the plenary and divisional sessions and 5 subject discussions were held.

In tallying up the results of the symposium, it was deemed necessary to hold regular (biannual) all-union symposia on combustion and explosion. It was also deemed expedient to request the directorate of the Physical Chemistry Institute of the Academy Sciences, U.S.S.R., to take upon itself the initiative in preparing for and calling the 2nd all-union symposium on combustion and explosion in 1970.

The participants and the organizing committee of the symposium addressed the Presidium of the Academy Sciences, U.S.S.R. with the request to set up a scientific council on problems of combustion and explosion for coordination of the research carried out in this field.

Profound recognition was expressed to the directorate and colleagues of the branch office of the Order-of-Lenin Institute of Physical Chemistry of the Academy of Sciences, for performing most of the work connected with the preparation and conduction of the symposium.

The work of the symposium proved to be creative and fruitful and made it possible to establish scientific contact between scientists engaged in research in the combustion and explosion fields. With the present issue, the journal begins publication of the principal information resulting from the symposium. To be given in the first few issues are review papers and reports of the combustion section. In the succeeding issues will be published reports of the detonation and kinetics sections.

Given below is a brief report of the combustion section (A. G. Merzhanov, Chairman).

The combustion section of the symposium was the most fully represented (107 reports) and covered the basic developmental trends of the science of combustion. The work was accomplished in the following subsections, which held their session simultaneously.

1. "Ignition" subsection (A. G. Merzhanov, Chairman; A. G. Strunina, Secretary). Eighteen reports were presented on the thermal explosion and ignition of condensed systems and gases. Of great interest were the reports of V. N. Viluinov, "Approximate Methods of Solving the Problems of the Thermal Theory of Ignition," of Yu. M. Gregor'ev, B. I. Khaikin, *et al.*, "On the Theory of Evaporation and Ignition of a Droplet of Explosive Material," and of B. A. Raizberg, "Physical Principles and Mathematical Model of the Process of Flame-Front Propagation over the Surface of a Charge of Solid Fuel during the Ignition Period." The reports relating to the thermal theory of ignition reflected the progress made in this field

in the last few years. At the present time a thermal model of the process has been developed in sufficient detail, and analysis of ignition characteristics within the framework of this model does not present any fundamental difficulties in the majority of actual cases. The majority of reports on thermal explosion was devoted to the little-studied aspects (degenerate regimes, the effect of vaporization, flow systems).

2. The subsection "Stationary Burning of Condensed Systems," (N. N. Bakhman, Chairman, V. A. Strunin, Secretary, 22 reports). Most of the papers were devoted to the experimental study of the burning characteristics of various types of condensed systems: composite systems (fuel+oxidizer), metal-containing systems, and individual explosives. Discussed in a number of papers were methods of controlling the burning rate of condensed materials by means of various chemical effects on the material (catalysts, penetrating radiation). In this connection, aspects of the burning mechanism and of chemical kinetics were broached in the reports and discussions. A separate session was devoted to reports on linear pyrolysis, a process which in some respects so initiates the burning process.

The methodological work of P. F. Pokhil, V. Mal'tsen, V. A. Seleznev, and I. V. Bavykin "Optical Method of Determining the Burning Surface Temperature of Condensed Systems," aroused considerable interest and lively discussion.

Two papers were of a theoretical nature. In the report of A. S. Shteinberg and V. B. Ulybin, an analysis was made of the various regimes of linear pyrolysis, while in the report of B. I. Kraikin, A. K. Filonenko and S. I. Khudiaev, the problem of flame propagation when two successive reactions take place in a gas was examined.

3. The subsection "Non-stationary Burning of Condensed Systems," (A. D. Margolin, Chairman, E. I. Maksimov, Secretary; 10 reports). The reports presented in this subsection can be conveniently divided into two categories: the nonstationary burning process and instability in the stationary burning regime. Very interesting in the theoretical reports of the first group (B. V. Novozhilov, O. Ya. Romanov) is the conclusion of vibrational (oscillatory) transition to a new stationary burning regime and the existence of self-oscillatory burning regimes. Unfortunately, experimentation in this domain was represented by only one report (O. I. Leipunskii, V. N. Marshakov) and the important theoretical results, as mentioned in the discussion, had not yet received the required experimental verification.

The second part of the reports treated various kinds of stationary burning instabilities: hydrodynamic instability of the burning of liquids, penetration of gas into slots and pores during the burning of porous substances, experimental observations of pulsating combustion. A survey report on these aspects was made by A. D. Margolin.

It is necessary to mention here the great progress made in the theoretical and experimental study of the filtration burning of porous substances, making it possible to set up quantitative relations for the cutoff limits of normal combustion. The reports on pulsating combustion of condensed systems (K. I. Senaiv, G. G. Shelukhin) instigated a lively discussion, indicating the divergence of opinion among researchers on the nature of this phenomenon.

4. Subsection "Combustion of Gases" (E. S. Shchetinkov, Chairman, K. G. Shkadinskii, Secretary), 22 reports were prevented on various aspects of gas burning (turbulent burning, hydrodynamic phenomena during burning, flame propagation, study of the overall kinetic properties of burning processes, theoretical aspects of flame inhibitors). Of great interest was the paper of V. P. Karpov and A. S. Sokolik

"On Shock-Wave Amplification during Interaction with a Flame of Cellular Structure," and of V. A. Kosterin, *et al.*, who carried out an interesting experimental and theoretical investigation of flame stabilization on jets.

5. Subsection "Diffusion and Heterogeneous Combustion," (L. A. Kliachko, Chairman, E. N. Rumanov, Secretary, 22 reports). Among the reports devoted to the various aspects of diffusion and heterogeneous combustion, two large groups can be singled out:

(a) Gas dynamics of the torch and boundary layer at the burning surface;
(b) Burning of metal particles.

Among the first group the greatest interest was aroused by the survey report of L. A. Vulis, "Outline of the Aerodynamic Theory of a Gas Torch", and the sharpest discussion was aroused by the report of V. P. Motulevich, V. M. Eroshenko, and Yu. N. Vorontsov, "Investigation of the Interaction of a Supersonic Jet of Chemically Active Gas and Carbon Particles." Extensive reports on the burning of metal particles were made by L. A. Gurevich, *et al.*, and L. A. Kliachko.

6. Mathematical subsection (A. J. Vol'pert, Chairman, S. I. Khudyaev, Secretary 13 reports). Most of the reports were devoted to numerical methods of solving various problems in combustion theory. Of greatest interest were the papers connected with hydrodynamic calculations, since problems in this area contain a number of difficult and as yet unsolved aspects. Interest was also aroused by the reports containing qualitative mathematical studies of differential equations describing various stationary processes.

In the opinion of A. I. Vol'pert, the meeting of mathematicians engaged in combustion and explosion problems at the Symposium was very useful and will further the future development of this important research direction.

In addition to discussion of the individual reports presented at the sessions of the subsections, three subject discussions on burning were held: "The Burning Mechanism of Condensed Systems" (F. I. Dubovitskii), "Unstable and Stationary Burning of Condensed Systems" (O. I. Leipunskii), and "Turbulent and Unstable Burning of Gases" (L. A. Vulis).

Conference on Kinetics and Thermodynamics in High Temperature Gases, NASA Lewis Research Center, Cleveland, Ohio, March 19, 1970.

Section: O
Subjects: High temperatures; Kinetics; NASA (Lewis); Thermodynamics

The following are authors' abstracts of papers presented at the meeting:

Chemical Equilibria

Sanford Gordon: "Complex Chemical Equilibrium Calculations"

Free energy minimization and equilibrium constant formulation—the principal methods used to calculate chemical equilibrium compositions—are reviewed and compared. In complex systems the former technique has distinct advantages. Differences in thermodynamic derivatives (such as specific heat and isentropic exponent) in reacting versus nonreacting systems are also discussed. (Section H)

Sheldon Heimel: "Calculation of Equilibrium Properties of Plasmas"

Unique problems encountered in calculating equilibrium properties of ionized gases are considered, including corrections due to coulombic forces and the effects of electronic excitation levels known to exist but not reported in the literature. Examples discussed include partially ionized hydrogen, helium, lithium, and the hydrogen-helium mixture anticipated on entry into the atmosphere of Jupiter. (Section H)

Frank J. Zeleznik: "Thermodynamics of the Internal Combustion Engine"

The thermodynamics of the Otto cycle are examined to assess the effects of varying degrees of idealization. (Section H)

Transport Phenomena

Richard S. Brokaw: "Transport Properties of High Temperature Gases"

A review is made of phenomena not usually encountered at moderate temperatures. Topics include thermal conduction in chemically reacting gas mixtures, the effect of the "unusual" intermolecular forces between labile atoms and/or free radicals, and some of the unique phenomena in ionized gases (plasmas). (Section I)

Charles E. Baker: "Experimental Measurement of Diffusion Coefficients for Atomic Oxygen"

Oxygen atoms from a microwave discharge diffuse to and recombine on a spherical catalytic surface. The measured heat flux to probes of different sizes is analyzed to obtain diffusion coefficients. Preliminary results of oxygen atoms diffusing through argon are presented. (Section I)

Roger A. Svehla: "Transport Properties of Complex Mixtures"

Problems associated with computing properties of multicomponent gas mixtures are discussed. The nature of the equations is indicated and sources of the many required cross sections are presented. Typical results are illustrated by calculation for the combustion products of jet fuel (kerosene) in air. (Section I)

Chemical Kinetics

Frank E. Belles: "Combustion Chemistry"

Current knowledge of the scheme of reactions responsible for the burning of hydrocarbons is reviewed. The crucial reactions are identified. The reliable measurements of their rates, most of which have been made at relatively low temperatures, are summarized. The shock-tube method of studying high-temperature rates is described. (Section H)

Theodore A. Brabbs: "Rate Constants from Ignition Studies of the H_2–CO–O_2 System"

A shock-tube study is presented in which the exponential growth of oxygen atom concentration is monitored via the blue CO flame band emission. By using four suitably chosen gas mixtures, the rates of the elementary combustion reactions $H+O_2 \rightarrow OH+O$, $O+H_2 \rightarrow OH+H$, $OH+H_2 \rightarrow H_2O+H$, and $OH+CO \rightarrow CO_2+H$ are determined in the range of 1000° to 1700°K. (Section H)

Marvin Warshay: "The Kinetics of the Dissociation of Bromine"

Precise shock-tube measurements of the reaction $Br_2+M \rightarrow 2Br+M$ (for M= helium, neon, argon, krypton, and zenon) are described. The results are used to test several recent theories; none is entirely satisfactory. (Section H)

David A. Bittker: "General Chemical Kinetic Computations for Multireactions System"

In systems of practical interest, many elementary chemical reaction steps often occur simultaneously. With a large computer the differential equations governing the chemical kinetics can be integrated numerically to obtain overall system behavior. Examples discussed include hydrogen peroxide production in a H_2–O_2 mixture and potential performance of B_2H_6–OF_2 as a rocket propellant. (Section H)

PUBLICATIONS

U.S. Navy Fire Research Bulletin, Vol. 1, No. 1 (September 1969) R. L. Tuve, Editor

Section: O

"The *U. S. Navy Fire Research Bulletin* is a quarterly periodical devoted to research and development efforts on a world-wide basis as they might affect the development and use of fire-fighting equipment and techniques of the U.S. Navy. Copies are available on request. Correspondence concerning the *Bulletin* and requests for copies should be addressed to the Editor."

Dr. R. L. Tuve
Code 6004
Naval Research Laboratory
Washington, D. C. 20390

This *Bulletin* provides summaries of fire research that are of interest to the Navy. It contains both abstracts and comments by the reviewer. This should prove a most useful service for the Navy fire community.

R. M. Fristrom, *Editor*, FRAR

Section: O

Federal Fire Council—Research Report Digests. Published at irregular intervals. First issue, January 1968; twelfth issue, January 1970.

"The members of the Committee on Research and Technology have determined that they might assist in the acquisition and dissemination of technical fire research reports by condensing them and helping to interpret them for members of the Federal Fire Council. Accordingly, you will find enclosed a condensed and modified technical report, the original writer of which is denoted after the title.

"In this condensation, some interpretations have been made by the person making the digest and observations are made of the more significant points of the research. Specific areas of application and use are suggested which we hope will be of importance to you.

"Readers interested in the original paper are referred to the library system references on the cover page. The committee would be happy to hear of your comments concerning this venture, which we hope may be worth continuing."—Richard L. Tuve, Chairman, Committee on Research and Technology

These reports are short summaries with comments by the one who summarizes. The source of the original material is indicated. The summaries provide excellent short one-to-two page critiques that should prove useful. The intent of the Digests is described in the quotation above.

R. M. Fristrom, *Editor*, FRAR

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THE NATIONAL ACADEMY OF SCIENCES is a private, honorary organization of more than 700 scientists and engineers elected on the basis of outstanding contributions to knowledge. Established by a Congressional Act of Incorporation signed by Abraham Lincoln on March 3, 1863, and supported by private and public funds, the Academy works to further science and its use for the general welfare by bringing together the most qualified individuals to deal with scientific and technological problems of broad significance.

Under the terms of its Congressional charter, the Academy is also called upon to act as an official—yet independent—adviser to the Federal Government in any matter of science and technology. This provision accounts for the close ties that have always existed between the Academy and the Government, although the Academy is not a governmental agency and its activities are not limited to those on behalf of the Government.

THE NATIONAL ACADEMY OF ENGINEERING was established on December 5, 1964. On that date the Council of the National Academy of Sciences, under the authority of its Act of Incorporation, adopted Articles of Organization bringing the National Academy of Engineering into being, independent and autonomous in its organization and the election of its members, and closely coordinated with the National Academy of Sciences in its advisory activities. The two Academies join in the furtherance of science and engineering and share the responsibility of advising the Federal Government, upon request, on any subject of science or technology.

THE NATIONAL RESEARCH COUNCIL was organized as an agency of the National Academy of Sciences in 1916, at the request of President Wilson, to enable the broad community of U.S. scientists and engineers to associate their efforts with the limited membership of the Academy in service to science and the nation. Its members, who receive their appointments from the President of the National Academy of Sciences, are drawn from academic, industrial and government organizations throughout the country. The National Research Council serves both Academies in the discharge of their responsibilities.

Supported by private and public contributions, grants, and contracts, and voluntary contributions of time and effort by several thousand of the nation's leading scientists and engineers, the Academies and their Research Council thus work to serve the national interest, to foster the sound development of science and engineering, and to promote their effective application for the benefit of society.

THE DIVISION OF ENGINEERING is one of the eight major Divisions into which the National Research Council is organized for the conduct of its work. Its membership includes representatives of the nation's leading technical societies as well as a number of members-at-large. Its Chairman is appointed by the Council of the Academy of Sciences upon nomination by the Council of the Academy of Engineering.

THE COMMITTEE ON FIRE RESEARCH functions within the Division of Engineering to stimulate and advise on research directed toward the development of new knowledge and new techniques that may aid in preventing or controlling wartime and peacetime fires. The Committee was established in December of 1955 at the request of the Federal Civil Defense Administration. It is supported by the Office of Civil Defense of the Department of the Army, the U.S. Department of Agriculture through the Forest Service, the National Science Foundation, and the National Bureau of Standards.

Volume 12 1970 Number 2

Fire Research Abstracts and Reviews

National Academy of Sciences

FIRE RESEARCH ABSTRACTS AND REVIEWS

FIRE RESEARCH ABSTRACTS AND REVIEWS will abstract papers published in scientific journals, progress reports of sponsored research, patents, and research reports from technical laboratories. At intervals, reviews on subjects of particular importance will be published. The coverage will be limited to articles of significance in fire research, centered on the quantitative understanding of fire and its spread.

Editor: Robert M. Fristrom, Applied Physics Laboratory
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Editorial Staff: Geraldine Fristrom, Emma Jane Whipple, Mary L. Swift

Volume 12 Number 2

Fire Research Abstracts and Reviews

Committee on Fire Research
Division of Engineering
National Research Council

NATIONAL ACADEMY OF SCIENCES
Washington, D. C.
1970

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FOREWORD

The Committee on Fire Research of the National Academy of Sciences—National Research Council has undergone a reorganization. Professor Howard Emmons has retired as chairman. He has given the committee distinguished leadership over the past several years, and he will remain with the committee to promote a smooth transition. The new chairman, Dr. Carl W. Walter of the Harvard Medical School, is a man of catholic interests and wide experience. The committee is fortunate to have obtained his services to guide it during this period of stress in science.

Retiring committee members are: Professor H. C. Hottel, Department of Chemical Engineering, Massachusetts Institute of Technology; Mr. George H. Tryon, Director of Membership Services, National Fire Protection Association; Dr. Richard L. Tuve, Consultant, U. S. Naval Research Laboratory; and Dr. Eric Wolman, Head, Traffic Systems Analysis Department, Bell Telephone Laboratories. These members have served the field of fire research well over the past years and your editor thinks that he speaks for all fire research workers in thanking them for their contributions.

New members of the committee include: Dr. William J. Christian of the IIT Research Institute; Dr. Robert M. Fristrom of the Applied Physics Laboratory, The Johns Hopkins University; Mr. James W. Kerr, Support Systems Division (Research), Office of Civil Defense; and Mr. Richard E. Stevens, Director of Engineering Services, National Fire Protection Association. They are all distinguished contributors to the fields of fire research and fire problems and should provide the committee a broad spectrum of views. These new members are most welcome.

This issue begins with a review of a survey of fire research facilities in the United States by Mr. T. Amrhein and Dr. H. Carhart. This survey was undertaken at the request of the Navy Laboratory Fire Research Panel and was endorsed by the Committee on Fire Research. It is planned to incorporate an updated version of this survey in the 1972 *Directory of Fire Research in the United States*. This survey provides an excellent picture of facilities available for the fire research in this country.

The outlook for fire research, although austere, is at least promising since scientific areas of social interest are receiving increasing attention. It is to be hoped that the recognition of this will ultimately lead to a balanced and expanded support of work in the area.

The Committee on Fire Research has arranged a program for an afternoon session at the 137th Annual Meeting of the American Association for the Advancement of Science to be held in December in Chicago in the 99th anniversary year of the Chicago Fire. It promises to be an interesting session. The scheduled program follows.

Are We Winning the War Against Urban Fires?

Arranged by

DR. CARL W. WALTER

Professor of Clinical Surgery, Harvard University

and

Chairman, Committee on Fire Research
National Academy of Sciences–National Research Council

CHAIRMAN: Dr. William J. Christian—*Underwriters' Laboratories, Northbrook, Illinois*

Saturday, December 26, 1970
2 p.m. Pick-Congress Hotel

Historic Fire Disasters

Mr. James W. Kerr—*Support Systems Division (Research), Office of Civil Defense*

New Techniques in Urban Fire Control

Chief Fire Marshal Curtis Volkamer—*Chicago, Illinois*

Urban Fire Protection: Studies of the New York City Fire Department

Dr. Edward K. Blum—*Project Director, The RAND Corporation, New York City*

Commingling of Urban and Forest Fires: A Case Study of the 1970 California Near Disaster

Mr. Carl Wilson—*Assistant Director, Pacific Southwest Forest and Range Experiment Station, U. S. Forest Service, Riverside, California*

Where Do We Go from Here?

Dr. Perry L. Blackshear, Jr.—*Professor of Mechanical Engineering, University of Minnesota*

Fires have taken an enormous toll of human lives and possessions since time immemorial. The increased complexity of urban life multiplies the potential hazards. This symposium will describe several important directions where new scientific and technological insights are beginning to have an effect to assure greater safety.

R. M. Fristrom, *Editor*

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G. Combustion Engineering

N. Instrumentation and Fire Equipment

O. Miscellaneous

Survey of Fire Research Facilities in the United States

T. AMRHEIN AND H. CARHART

Naval Research Laboratory, Washington, D.C.

To reduce significantly the extent of fire damage and personnel injuries experienced by operational units within the U.S. Navy, Dr. Joel Lawson, Director of Navy Laboratories, on 14 April 1969, established the Navy Laboratory Fire Research Panel for the purpose of mounting a cohesive Navy-wide laboratory effort in basic and applied research.

In addition to determining the status of the ongoing programs and the need for new programs in fire research, Dr. Homer Carhart of the Naval Research Laboratory, as chairman of the Panel, and Dr. John Huth, acting for Dr. Lawson, thought there was a need for determining what facilities were available within the research establishment for carrying out such programs. Some excellent information existed as a result of Professor Howard Emmons' "Fire Research—A Trip" report of 1966–1967, but it was considered that a further survey was needed to update Dr. Emmons' work and to provide a more detailed look at the facilities existing within the United States.

Since the results of such a survey would be mutually beneficial to both the Panel, in its work, and the members of the fire research community in general, the format of the survey questionnaire was coordinated with Professor Emmons and the members of the Committee on Fire Research of the National Academy of Sciences—National Research Council. The categories of interest included such items as *Major Test Structures*, *Outdoor Test Facilities*, *Simulation Facilities*, *Completely Confined Spaces*, *Instrumental Capabilities*, and *Data Analysis*. A category entitled *Plans and Recommendations for Future Facilities on Extending Capability of Present Facility* was included to make the survey results relevant for near-term facility modifications.

To date, 154 questionnaires have been sent to military laboratories, university laboratories, private and industrial laboratories, and fire safety schools. One hundred eleven of these organizations have responded with 48 indicating existing facilities of some nature. The response has been most gratifying, and the results are published here in a Fire Facilities Matrix which shows the types of facilities and the distribution of these types. Because of space limitations, it is not possible to publish the detailed replies; a method of publishing this information is being explored.

Much effort is expended in keeping track of the planned or ongoing programs in the broad area of fire research. Such publications as the *Directory of Fire Research in the United States*, the *Fire Research Abstracts and Reviews*, the *U.S. Navy Fire Research Bulletin*, etc., are directed towards disseminating information about programs to the research community. Not nearly as much effort has been expended in providing similar information on the availability of fire research facilities. It was to this end that the survey was planned and coordinated. No attempt is made to comment on the completeness of the survey, since, on the contrary, the results can represent at best only part of the total facilities in existence. An effort will be made to update and expand the information to include those organizations not reached by the original questionnaire. Such organizations are invited to submit statements describing their fire research facilities (format forms will be sent upon request).

That there is a need for such a survey to be continued on a periodic basis becomes more clear in light of the environmental controls being placed on the operations of commercial and private companies, and fire research laboratories. The great majority of the responders have no provisions for air pollution abatement devices to eliminate or at least control the products of research fires. The further enactment of laws and enforcement of restrictions could seriously hamper the operations of many organizations in fire research, if not eliminate them altogether. This problem is one which rightfully involves the fire research community as a whole. As such, we must address ourselves to it with candor and imagination.

Following is a list of the laboratories that reported and the name of the person to contact for more detailed information.

We would like to thank Dr. R. M. Fristrom for his interest and cooperation.

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Dr. Homer W. Carhart

Naval Ship Research and Development Laboratory
Annapolis, Maryland 21402
Mr. Robert Foernsler

Naval Weapons Center
China Lake, California 93555
Dr. Alvin S. Gordon or **Mr. Warren K. Smith**

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Dahlgren, Virginia 22448
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Belleville, New Jersey 07109
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FIRE FACILITIES MATRIX

Organization	Major test structures	Outdoor test facilities	Standard fire test facilities	Simulation facilities	Completed confined spaces
Department of Defense					
Aero Propulsion Laboratory, Wright-Patterson AFB	×	×	×	×	×
Army Mobility Equip. Command, Fort Belvoir	×				×
Naval Air Propulsion Test Ctr.	×			×	×
Naval Air Test Center				×	
Naval Civil Engrng. Lab.	×				×
Naval Research Laboratory	×	×			
Naval Ship R&D Laboratory, Bayonne Fire Research Sta.	×	×			
Naval Weapons Center	×	×	×	×	×
Naval Weapons Laboratory		×	×	×	
Other Government Agencies					
Department of Agriculture, Forest Products Laboratory			×		×
Department of Agriculture, Forest Service Regional Laboratories	×	×			×
Department of Agriculture, Southern Utilization R&D Division			×		
Department of Interior, Bureau of Mines	×			×	×
FAA—National Aviation Facilities, Experimental Center	×	×	×	×	
NASA—Lewis Research Center				×	
National Bureau of Standards	×		×	×	
University Laboratories					
Harvard University	×				×
Massachusetts Institute of Technology					×
Penn State University (Ordnance Research Laboratory)		×			
State University of New York at Stony Brook					×
University of California, Lawrence Radiation Laboratory		×		×	×
University of Maryland, Fire Service Extension Dept.	×	×			
University of Minnesota	×			×	
University of Montana		×			
University of Oklahoma (Flame Dynamics Laboratory)	×		×		×
University of South Carolina				×	
Washington State University		×			×

Organization	Major test structures	Outdoor test facilities	Standard fire test facilities	Simulation facilities	Completed confined spaces
Private and Industrial Laboratories					
Ansul Corporation		×		×	×
Arthur D. Little, Incorporated		×	×	×	×
Automatic Sprinkler Corporation				×	
Battelle Memorial Institute		×			×
Boeing Corporation (Seattle)		×		×	×
Boeing Corporation (Wichita)		×			
Chemstrand Research Center			×		
Dikewood Corporation		×			
E. I. duPont de Nemours and Company			×		
Electric Boat Corporation, General Dynamics Corp.	×				
Factory Mutual Research Corporation	×	×	×	×	×
Falcon Research and Development Corporation		×			
IIT Research Institute	×	×	×		
National Foam Systems, Inc.	×	×			
Portland Cement Association	×		×		
Safety First Corporation		×		×	
TRW Systems		×			
Underwriters' Laboratories, Inc.	×	×	×		
URS Corporation	×				
Walter Kidde and Company	×	×		×	

Central Co-Ordination of Test and Research at Bad Oldesloe*

R. G. SILVERSIDES

Fire Research Station, Borehamwood, England

Section: O
Subjects: Bad Oldesloe; Fire tests; Fire research

This report contains an account of the official opening of a new research and testing laboratory of the Forschungsgemeinschaft Brandschutz in Bad Oldesloe, Germany. A brief account of the circumstances leading to its erection, its purpose and the experimental facilities it incorporates, is given.

In June 1968 the Forschungsgemeinschaft Brandschutz (Fire Protection Research Association) announced the completion of a new laboratory for the testing of sprinklers and other means of fire extinction. The laboratory was later officially opened by Prof. Dr. Ernst Schneider, President of the German Congress of Industry and Commerce. The official opening, presided over by Dr. Wittenburg, Head of Selbstättige Feuerlöschanlagen GmbH (commonly known as SFH), was attended by approximately 60 representatives of German industry, government, universities and other organisations concerned with problems of fire protection, as well as a representative from each of the Fire Research Station and Fire Offices' Committee.

The initiative for building the new laboratory had come from SFH which, in collaboration with a small number of other firms, had established the Forschungsgemeinschaft Brandschutz to operate and control the new laboratory. The intention is to offer the facilities of the laboratory, not only to members of the Forschungsgemeinschaft but to any other potential users on a repayment basis.

Fragmented Effort

Prof. O. Herterich (Director of the Vereinigung sur Förderung des Deutschen Brandschutzes e.v.), the principal guest speaker, outlined the history of fire protection research in Germany which was seen to be a fragmented effort, distributed over about 20 laboratories, each concerned with some aspect of fire research, and with no central co-ordination. Prof. Herterich compared this fragmented effort with the co-ordinated research and testing facilities in some other countries, including the United Kingdom.

The current effort, as distributed between 20 laboratories, was said to be: 4,975 scientists; 5,000 engineers; 6,025 assistants; and 1,475 student assistants, at a total annual cost of approximately DM6.7 million, of which DM2.6 million represents the cost of personnel. The theme of Dr. Herterich's remaining remarks was the desirability of co-ordination of fire research with State and, if possible, insurance support.

The Acting Director of the Forschungsgemeinschaft laboratory, Herr Job, who spoke next, also emphasized the importance of central direction of fire research and testing. Four firms have joined together to form the Forschungsgemeinschaft Brandschutz and it is proposed to offer a service, on repayment, to all comers. Fire protection falls broadly into two categories—preventive and remedial—and in Herr Job's opinion relatively too much of the available effort is currently devoted to preventive measures. It is accordingly his intention to emphasize the remedial side, viz, fire fighting, extinction.

Bad Oldesloe Laboratory

In the flexible building provided for the purpose, it is the intention to establish conditions where both research and testing can be carried out. The laboratory is presently equipped for work on sprinklers, where the main concern is to determine the effectiveness of sprinklers in controlling fires in high-stacked goods. Two high-expansion foam generators (each capable of producing 450 m^3/min or about 15 000 ft^3/min of 1,000:1 high-expansion foam) are available and there is provision for extinction tests using carbon dioxide and high pressure water.

A further main line of investigation will be the corrosive effects of products of combustion of halogen-containing plastics, in particular pvc. There have been a number of fires in Germany in which the reinforcement in concrete is said to have been severely corroded by HCl, a problem which is causing widespread concern in the country.

Future plans for the Forschungsgemeinschaft include open site work on oil fires—a monitor for foam and water is provided for this purpose on the roof of the new laboratory—and on the toxic and corrosive products of new building materials. A further laboratory is planned—it was said that a start would be made on this within the next month or two—the dimensions of which would be 20 m$\times$40 m$\times$6 m high and this would be used for fire tests on plastics, as well as sprinklers, detectors and extinguishers. The planned new laboratory is to be sited adjacent to the existing laboratory and the two are to be connected by a 10 m wide viewing gallery which will have two-directional viewing and from which experiments in both laboratories will be capable of being observed.

The external frame of the new building is of RSJs on a 5 m module, strapped horizontally at 2.4 m intervals, and with a roof frame also of RSJs but of lighter caliber, at 5 m intervals in one direction and 2.5 m in the other. At various points there are diagonal strengtheners. The cladding is of galvanised corrugated sheet steel, internally fixed to form both walls and roof.

Sections A and B, each of floor area 10 m$\times$10 m and of height respectively 12 and 4 m, comprise the experimental area. There is no partition between A and B. Section C, 5 m$\times$10 m$\times$4 m high, is the instrument and control room.

Access from Section C to Section B is by personal door and good visibility is provided via an observation window, virtually the whole width of the partition between them. A similar observation window is provided at the far end of A for viewing from outside. Access from outside is by four double doors, one each in Sections A and C and two on opposite sides of B, the dimensions of which are approximately 3 m$\times$2.5 m high.

There is no provision for access to the upper parts of the building other than ladders and a portable beanstalk; nor has lifting gear been installed, but a forklift truck is available.

There is a public address system, both inside and outside the building, with a trailing microphone lead long enough to allow the speaker to be located anywhere inside or within reasonable distance outside the building. The outside of the experimental parts of the building is provided with a water cooling system capable of delivering 1,800 litres/min either directly from the town main, or by means of an electric pump from a static water tank. A reserve pump operated by an internal combustion engine is available in case of emergency resulting from an electricity failure.

Provision for ventilation and smoke clearance of the building is by means of smoke vents, four on each side of Section A (just below ceiling level) of dimensions approximately 1 m×1.5 m. These are manually controlled from the outside. The foam generator fans are also used for smoke clearance. There is no provision for storage of equipment and no special drainage facilities, nor provision for foam dispersal. Six-tier racks, reaching to the top of Section A, are to be used for high-stacked storage experiments.

Facilities

The laboratory is provided with installation for the following:

Sprinklers: Liberal provision for the placing of pipe-work in Sections A and B for sprinkler installation. Capacity 120 litres/min.

Water curtain between Sections A and B: Capacity 60 litres/min.

High pressure water spray: Capacity 80 litres/min at 8 atm.

CO_2 extinction: A 3,000 kg CO_2 holder is located in a lean-to on one side of Section C, to hold liquid CO_2 at −20°C and 20 atm. From this, CO_2 can be piped into Sections A and/or B, and also into a further small experimental room—which is no more than a wooden hut 9 m×4 m×2.5 m high, divided into two compartments—in which actual fire experiments with CO_2 extinction are carried out. Ten seconds before the release of CO_2 an audible warning is sounded to warn personnel to evacuate.

Water/foam monitor: Roof mounted (on A) for field tests on liquid fires. Capacity 1,600 litres/min.

High-expansion foam: Two 1,000:1 Hi-Ex foam generators, each of capacity 450 m^3/min feed foam into Section A. One is located at ground level, the other at 4–5 m, situated on the roof of Section B.

The measurement and control facilities, which are neither extensive nor sophisticated, are housed in Section C of the building. The operator sits at a console, where the operation of the various experimental facilities can be controlled, and recording meters read, and to which a good view of Sections A and B is presented through the observation window. A series of pressure gauges indicates compressed air pressures on all lines via which operation of sprinklers, etc, are remotely controlled.

Simple temperature indicators and a temperature recorder present the air temperatures measured at 10 positions at about 10 cm below the ceiling in A, and a further 10 in B. Each position has two thermocouples to allow for simultaneous recording and visual monitoring. There is no provision for measuring structural temperatures, nor has any calculation been made of temperatures likely to be reached on the structure.

The new laboratory belongs to the Forschungsgemeinschaft Brandschutz which is still very young and at present has no staff of its own. The immediate intention appears to be to run the laboratory with SFH staff and effort, Herr Job being temporarily in charge. It is eventually intended to appoint a Director, with about six technicians and six assistants, but the plans for staffing seem to be rather fluid at present.

The whole project had been conceived and designed in four months, and building operations completed in a further four months, i.e., eight months in all. In contrast to this remarkably short time the cost, DM250,000 (equivalent to £25,000) seemed to be relatively high. It provides a useful facility, erected primarily to meet two urgently felt needs, viz. to study the problems of high-stacked storage and the corrosive effects of halogenated products of combustion from plastics materials. It has, naturally, some limitations, and when used to study a wider variety of problems, no doubt the need for some improvisation will be felt. Despite this it is a striking example of what can be achieved in a very short time when a need is clearly seen, and the action rests in the hands of men with drive and initiative. They are to be congratulated on a very substantial achievement.

ABSTRACTS AND REVIEWS

A. Prevention of Fires and Fire Safety Measures

Adley, F. E. and Uhle, R. J. "Protection Factors of Self-Contained Compressed-Air Breathing Apparatus," *Am. Ind. Hyg. Ass. Jnl.* **30** (4), 355–359 (July–August 1969)

Section: A
Subjects: Breathing apparatus; Compressed air masks; Protection factors in breathing apparatus.

Abstract by Safety in Mines Research Establishment, England.
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A comparison of protection factors for several makes of self-contained breathing apparatus in the demand and pressure-demand modes are given. Protection factors were determined by quantitatively measuring the in-mask concentration of a test gas. The protection factors obtained illustrate the wide range of mask leakage occurring with various facial shapes and how these are influenced by such factors as talking, the wearing of spectacles, deep breathing and head movement. The test methods are also described.

Blumhagen, H.-J. "Fires and Accidents in Electrical Installations—Preventive Measures," *Moderne Unfallverhütung* (13), 23–28 (1969). In German.

Section: A
Subjects: Accidents; Electrical installations; Fires; Preventive measures; Safety

Abstract by Safety in Mines Research Establishment, England.
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Examples are given of fires caused by heating of current-carrying conductors, by electric arcs due to short-circuits, by failures of control devices, by the use of standard electrical equipment where special equipment or protective measures should have been used, and by high currents where the insulation was damaged and/or the prescribed additional protective measures were lacking, and the causes of these accidents are discussed. The regulations governing the use of electrical equipment in Germany are listed and the arrangements for the testing and monitoring of such equipment are briefly described.

Bowes, P. C., Field, P., and Ramachandran, G. (Joint Fire Research Organization, Borehamwood, England) "The Assessment of Smoke Production by Building Materials in Fires. 3. The Effect of Relative Humidity on Measurements of Smoke Density," *Joint Fire Research Organization Fire Research Note No. 775* (June 1969)

Section: A
Subjects: Building materials; Fire propagation test; Relative humidity; Smoke

Authors' Abstract

It has been shown that the relative humidity of the ambient atmosphere can sometimes affect significantly the optical density of the smoke produced by materials in the fire propagation test apparatus.

Some control of the relative humidity in the test chamber will be necessary for the purposes of a standard test for smoke production.

Calzia, J. "Les Substances Explosives et Leurs Nuisances (Explosive Substances and Their Harmful Effects)," *Paris, Dunod* (1969) 344 p.

Sections: A, K
Subjects: Blast; Detonations; Explosives; Harmful effects; Safety; Shock; Toxicity

Abstract by Safety in Mines Research Establishment, England.
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General. Detonation waves. Determination of characteristics of explosives. Effect of explosives. Propagation of shock wave. Effects of shock. Effects of blast. Methods of initiation. General safety regulations against poisoning, static electricity, fires, etc.

Chevalier, M. and Tisserand, A. "Oxygen. Properties, Dangers, Preventive Measures," *Cah. Notes Docum. Inst. Natn. Sécur. Prév. Accid. Travail* (56) No. 648 (3rd Quarter 1969). In French.

Section: A
Subjects: Danger, oxygen; Oxygen; Preventive measures; Properties of oxygen; Safety

Abstract by Safety in Mines Research Establishment, England.
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After listing the characteristics of oxygen and of its combustion the authors describe accidents involving oxygen at normal pressure, high-pressure oxygen and

liquid oxygen. They discuss the reaction of various metals to high-pressure oxygen and the ignition temperatures of various materials in oxygen.

Gehm, K. H. and Bittner, G. "The Use of Foreign Explosion-Proof Electrical Equipment in the German Federal Republic," *PTB Mitteilungen* **79** (2), 96–97 (April 1969). (SMRE Transl. No. 5781)

Section: A
Subjects: Electrical equipment; Explosion-proof; Germany; Regulations

Abstract by Safety in Mines Research Establishment, England.
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This paper explains the ordinances and regulations governing the use, in hazardous areas, of explosion-proof electrical equipment produced in accordance with foreign specifications.

Griffin, O. G. and Longson, D. J. "The Hazard Due to Outward Leakage of Oxygen from a Full Face Mask," *Ann. Occup. Hyg.* **12** (3), 147–149 (July 1969)

Section: A
Subjects: Face mask; Hazard; Leakage; Mask; Oxygen

Abstract by Safety in Mines Research Establishment, England.
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Oxygen leakage from full face masks was determined over the range of pressure likely to be found in breathing apparatus fitted with a manual relief valve. Experiments have shown that when this type of apparatus is worn with two of the four types of face mask examined, the outward leakage may be sufficient to create a flammability hazard. The leakage is less from the other two types of face mask, both with a cushion seal, and likely to be harmless provided the pressure in the mask does not exceed about 1.2 kN/m^2 (12 cm water gauge). On the particular breathing apparatus used, the relief valve has an extremely high resistance to flow which results in substantial leakage from all four types of mask when the relief valve is operated. The rapid ignition of human hair and the face mask was found to occur at oxygen leakage rates as small as 0.25 l/min. This work confirms the need for care in the choice of full face masks, the importance of correctly fitting the mask to the wearer and the advisability of using breathing apparatus supplied with a well designed automatic relief-valve.

Hager, N. E., Jr. (Armstrong Cork Company) "Calculation of Performance of Fire Retardant Ceiling Systems—Part II," *Fire Technology* 6 (1), 52–58 (1970)

Section: A
Subjects: Ceilings; Fire retardants; Retardants

Reviewed by A. A. Brown

This is a companion article to Part I which appeared in *Fire Technology* in November 1969. It serves as a follow-up in the same publication in 1970. Both are concerned with the thermal behavior of a composite system frequently used in structures, consisting of a noncombustible ceiling board suspended below a concrete floor slab.

In Part I a series of equations was developed to describe the heating of the concrete and the ceiling board when subjected to standard furnace tests. These were based on available information on the thermal properties of these materials. Thermal conductivity values for tile were obtained by measurement during the study. Those for concrete and the specific heat for both were based on published values. Thermal diffusivity was obtained by computation and emissivity values for both were taken from a curve for silicates.

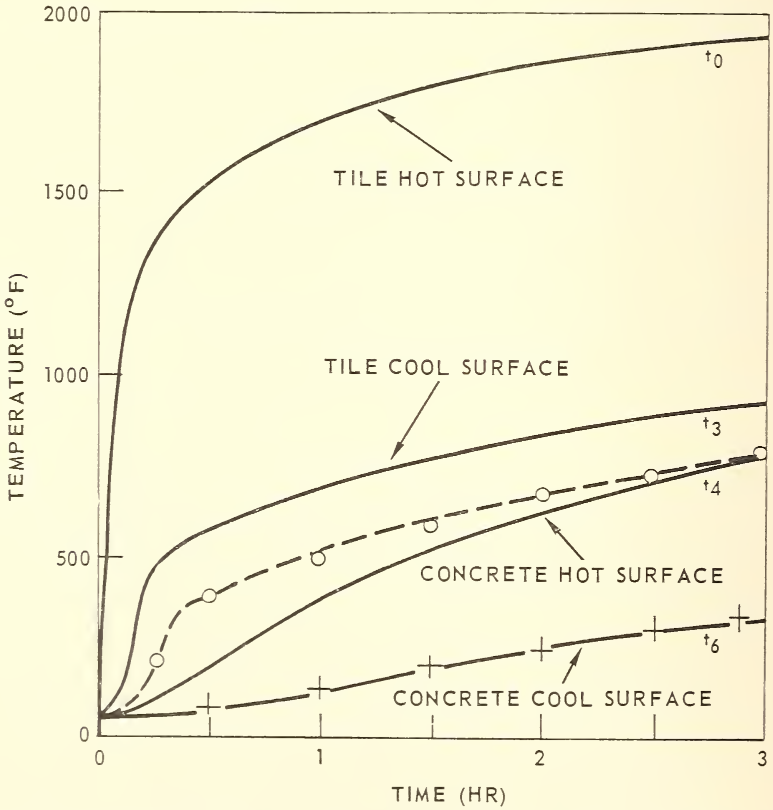

FIG. 5. Performance of Assembly No. 3 exposed to standard fire test. Computed results are represented by solid line curves, experimental temperature values at concrete cool surface by crosses, and experimental temperature values at steel joist by circles and dashed-line curve.

When these values were substituted in the equations to describe time-temperature relationships the computations became slow and laborious. This article describes the use of an IBM 1620 computer to carry out the computations. Besides its value in greatly speeding up the operation, it has a special value in permitting the programmer to determine the curve of best fit for a particular heating regime.

Complete computations enabling the construction of a series of curves were carried out for two slab ceiling assemblies. That for Assembly No. 3, designated Fig. 5 in the article, is repeated on p. 118 for illustration.

The author cautions that though computations of this kind by computer can be of great practical value in selecting materials and systems for optimum performance, they do not eliminate the need for experimental testing, since factors other than heat transfer are often critical.

Helwig, N. and Nabert, K. "Safety Distances between Parallel Pipelines for Flammable Liquids and Gases," *PTB Mitteilungen* **79** (2), 97–101 (April 1969) (SMRE Transl. No. 5751)

Section: A
Subjects: Gases; Flammable gases; Flammable liquids; Safety; Pipelines

Abstract by Safety in Mines Research Establishment, England.
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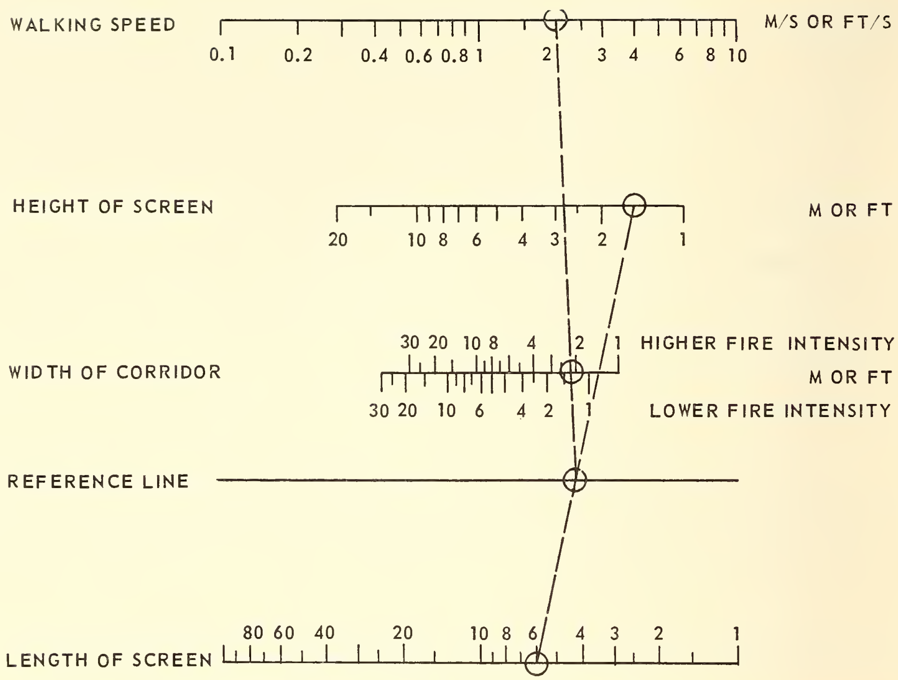
In parallel pipelines, the danger exists of mutual interference in the case of disturbances. By analyzing the few accident reports available, the authors assess the effects of fires and explosions and the mechanical effects of the emerging liquids and gases. With underground pipes—which is the best arrangement from the safety point of view—there is the risk of serious damage to parallel pipelines, mainly as a result of a gas pipeline bursting. On the basis of experience gained so far, on the dimensions of the cavity created when the gas pipe bursts, provisional figures are given for the safe distance between parallel gas and liquid pipelines as a function of the diameter of the pipes.

Law, Margaret (Joint Fire Research Organization, Borehamwood, England) "Nomogram for the Width of an Escape Route Bordered by a Wired Glass Screen," *Joint Fire Research Organization Fire Research Note No. 765* (April 1969)

Section: A
Subjects: Building; Escape means; Glazing-Wired; Movement; Radiation; Safety

Nomogram by Author

A nomogram for the width of escape routes bordered by wired glass screens is given and the method of calculation is described.



NOMOGRAM FOR THE WIDTH OF AN ESCAPE ROUTE BORDERED BY A WIRED-GLASS SCREEN

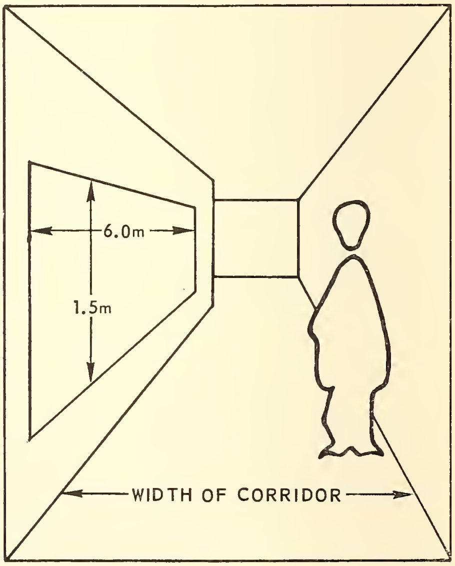
Example illustrated on nomogram

A corridor is bordered by a wired-glass screen 1.5m (5ft.) in height and 6.0m (20ft.) long (Figure 2). What is the minimum width of the corridor for a person walking at an average speed of 2.0m/s (6.7ft./s) ?

Step 1: Draw line from intersection on reference line to walking speed (= 6) to height of screen (= 1.5). Note intersection on reference line.

Step 2: Draw line from intersection on reference line to walking speed (= 2). Note intersection on width of corridor scale.
Width = 2.2m for higher fire intensity
= 1.35m for lower fire intensity
(Using the nomogram in terms of feet gives corridor widths of 7ft. and 4.5ft. respectively.)

If people using the corridor were forced to move much more slowly, say at 0.2m/s, the minimum corridor width would be 5.8m at higher fire intensity and 3.7m at lower fire intensity. If it is not practical to have such a width the glazed area must be reduced, or at least be well above floor level to allow people to crouch down to escape the radiation. If width and length of corridor are known, the reverse procedure will give permissible height of glazing.



CORRIDOR BORDED BY WIRED-GLASS SCREEN

Vidlicka, M. "The Effect of an Electric Arc on the Safety of a Flameproof Enclosure. Introduction of a Technique for Testing Sand- and Oil-Filled Enclosures," *Vedeckovyzkummy Uhelny Ustav Zprava* (63) 24 p. (1969). In Czech.

Section: A
Subjects: Arc; Electric arc; Flameproof enclosure; Safety; Tests

Abstract by Safety in Mines Research Establishment, England, from author's summary. Reprinted by permission.

This report contains instructions for the practical testing of sand- and oil-filled enclosures to be carried out at the short circuit testing station of the VVUU, as prescribed by Czechoslovak Standard CSN 34 1480 "Explosionproof electrical equipment." The testing methods and equipment have been tried and the team working at the testing station have acquired sufficient experience in their use to be able to perform, with a minimum of time needed for preparation, all the tests which may be required in Czechoslovakia.

B. Ignition of Fires

Guney, M. "The Moisture Factor in the Spontaneous Heating of Coal," *Min. Dep. Mag. Univ. Nott.* (21), 35–47 (1969)

Section: B
Subjects: Coal; Heating, spontaneous; Ignition, spontaneous; Moisture; Spontaneous heating

Abstract by Safety in Mines Research Establishment, England. Reprinted by permission.

Describes investigations carried out in the simulated mine conditions in the laboratory of the influence of moisture on the spontaneous heating of coal. The object of this investigation has been to determine relative tendencies of certain coals to spontaneous heating under adiabatic conditions and to study the character, quantity and properties of gaseous products evolved as a result of oxygen sorption and to analyse the significance of the carbon monoxide to oxygen deficiency ratio of the generated products.

Rumanov, E. N. and Khaikin, B. I. "Critical Self-Ignition Conditions for a Combination of Particles," *Physics of Combustion and Explosion* **5**, 129–136 (1969)

Section: B
Subjects: Particles; Self-ignition

Authors' Summary—Translated by L. Holtschlag

A theoretical study is made of the critical self-ignition conditions for a gas-flow suspension of solid particles or liquid droplets. The critical conditions have the same form as those for a single particle, except that the heat transfer coefficient is replaced by an effective heat transfer coefficient, for which an explicit expression is found. The mutual effect of the particles is determined by the magnitude of a parameter A, which is inversely proportional to the square of the mean size of the particles. The model considered here, with the effective heat-transfer coefficient, explains the qualitative features of the dependence of the ignition temperature on the concentration for particles of different size (as measured by Cassel and Liebman) and also the complex (with maximum and minimum) dependence of the ignition temperature on particle size.

Schlebeck, E. and Marold, G. "Ignition Hazards during the Use of High Pressure Oxygen," *ZIS Milleilunger* **9** (10), 1445–1446 (October 1967). SMRE Transl. No. 5785.

Section: B
Subjects: Hazards; High pressure; Ignition; Oxygen

Abstract by Safety in Mines Research Establishment,England.
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Commenting on the factors which increase the ignition hazards the authors list twenty-three materials which were tested at ZIS (Zentral Institut für Schweisstechnik) in 1965–1967 and which were found to be oxygen resistant in the given test conditions.

Stikachev, V. I. and Zubkov, P. N. "Causes of Firedamp and Coal Dust Ignition," *Bezopas. Truda Prom.* **13** (8), 19-21 (August 1969). In Russian.

Section: B
Subjects: Coal dust; Dust, coal; Explosions; Firedamp; Ignition; Methane

Abstract by Safety in Mines Research Establishment, England.
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A detailed analysis of explosions in the main mining regions has shown that the majority of ignitions and explosions have taken place in development workings

due to: a) formation of explosive gas concentrations as a result of inefficient ventilation, i.e., stoppage of auxiliary ventilation fans, insufficient amount of air delivered into difficult to ventilate faces, etc. b) detonation products blown into gassy areas, transfer of detonation flame through cracks in coal, detonation without stemming, etc. c) sparking in the detonation circuit due to usage of alternating current and faulty detonating equipment.

Tanaka, R. "Basic Study of Intrinsically Safe Circuits for Methane-Air Mixtures under Hyperbaric Pressure," *Rep. Res. Inst. Ind. Saf.* (Japan) **17** (7), 14 p. (March 1969). In Japanese.

Sections: B, A
Subjects: Air-methane; Circuits-safe; Electrical circuits-safe; Hyperbaric; Methane-air

Abstract by Safety in Mines Research Establishment, England, from English summary. Reprinted by permission.

The minimum ignition limits in low-voltage inductive, resistive and capacitive circuits are determined with methane-air mixtures at above atmospheric pressure, using the IEC type spark-producing apparatus. In inductive circuits the minimum igniting current decreases with increasing pressure and reaches its lowest value at a pressure depending on the circuit inductance; after that the m.i.c. begins to increase with the pressure. In resistive circuits the m.i.c. also decreases at first with increasing pressure and the lowest value is attained at 4 kg/cm^2. After this the m.i.c. increases with the pressure and flattens out at 10 kg/cm^2 or more. The minimum igniting voltage of capacitive circuits is shown to decrease steadily with increasing pressure, eventually reaching a constant value corresponding to the capacitance, which is smaller than that at atmospheric pressure. The curve flattens out at pressures greater than 10 kg/cm^2. Problems of designing and testing intrinsically safe circuits with mixtures at more than atmospheric pressure are discussed. The variation of duration of oscillatory discharges with pressure under particular inductive-circuit conditions are appended.

Tanaka, R. "The Minimum Igniting Currents for Explosive Gas- or Vapour-Air Mixtures by Break-Sparks in Low Voltage D.C. Inductive Circuits," *Rep. Res. Inst. Ind. Saf.* (Japan) 17 (6), 11 p. (March 1969). In Japanese.

Section: B
Subjects: Current ignition; Explosive gas; Gas, explosive; Ignition; Inductive circuits; Low voltage ignition; Minimum ignition; Sparks; Vapor, explosive

Abstract by Safety in Mines Research Establishment, England, from English summary. Reprinted by permission.

The IEC type apparatus was used and in addition the test circuit consisted of a battery, an air-cored inductance and a non-inductive variable resistance. The air-cored inductances ranged from 0.1 mH to 10 H in 6 steps. The apparatus is calibrated before and after each determination of minimum igniting current and if the performance is found to have changed the apparatus is brought back to a standard calibration. A table gives a comparison of the most easily ignitable concentrations of mixtures by break sparks of 95 mH inductance at 24 volts d.c. and the minimum igniting currents obtained with the IEC apparatus and the Breakflash No. 2. The ratio of the minimum igniting current for each combustible between the two are 2.95 for hydrogen, 2.17 for ethylene and 1.6 to 2.0 for the others. The effect of the value of the inductance on the most easily ignitable concentration is examined for hydrogen, methane and ethylene. With a circuit voltage ranging from 6 to 96 volts d.c., the minimum igniting currents I for the various air-cored inductances L are determined and although the results are basically given in the form of $LI_n = \text{const}$, the deviation of the data from the equation occurs with smaller inductances. Where the circuit voltages are more than 48 V, an inductance less than about 3 mH has little effect on the minimum igniting current for hydrogen and methane. The effect on the minimum igniting current of spark suppressors such as shunt ohmic resistors, a non-linear resistor, air condensers and rectifiers are also briefly examined.

Tanaka, R. "Fundamental Study of Testing Apparatus for Determining Minimum Igniting Currents for Explosive Gas Atmospheres," *Rep. Res. Inst. Ind. Saf.* (Japan) **17** (5), 10 p. (March 1969). In Japanese.

Section: B
Subjects: Explosive gases; Gases, explosive; Ignition; Minimum ignition; Tests, ignition

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The author has investigated the minimum igniting current in low voltage inductive and noninductive circuits using a copper wire snapping wire apparatus having a high separation speed and little quenching effect of the electrodes in order to cover accidents where the wire breaks. The results are compared with those of the IEC apparatus, the Breakflash No. 3 with ignition sensitivity similar to that of the ERA No. 2 apparatus, and the Intermittent Break apparatus used by SMRE. For noninductive circuits the use of the IEC apparatus to determine the minimum igniting current is limited to more than 20 V and within this limit the ignition sensitivity of the IEC type is shown to be the highest. Up to about 20 V the copper wire snapping wire apparatus is more sensitive to ignition than the Intermittent Break apparatus. The electrode materials of the IEC apparatus are also discussed. The cadmium disc is replaced by an iron, nickel or brass electrode and each minimum igniting current is compared. For inductive circuits with larger inductances the minimum igniting currents are nearly the same, while differences between them gradually appear when the inductance is decreased. For inductive circuits with no arc discharge the minimum igniting current does not depend upon the polarity. For noninductive circuits

the minimum igniting current of a circuit at 48 V increases by about 20% with a cadmium anode and tungsten wire cathodes. When the cadmium is replaced with iron there is no effect of reversing the polarity.

Walker, I. K., Harrison, W. J., and Read, A. J. (Department of Scientific and Industrial Research, Wellington, New Zealand) "The Effect of Dry Heat on the Ignition Temperature of Cellulose," *New England Journal of Science* **12,** 98–110 (1969)

Section: B
Subjects: Cellulose; Dry heat; Ignition temperatures

Reviewed by F. L. Browne

Experiments described, a discussion and 59 references show that prolonged heating of cellulose in dry air above 148°C can lower the temperature at which it can ignite. This may explain the spontaneous combustion of cellulosic materials, including wood, after long times at temperatures below 180°C. Even below 100°C there may be a low hazard of spontaneous combustion. This would be ignition in the solid phase rather than the usual ignition in a gas phase evolved by prior pyrolysis at 400° to 600°C.

Experiments were made with acetone-extracted viscose rayon, with medical-grade cotton wool, and with shredded filter paper. The cellulose was packed in a stainless steel right cylinder 19.7 cm in internal diameter by 20.4 cm high. The bulk density (dry) was 0.086 g/ml for rayon, 0.101 for cotton wool, 0.149 for filter paper. The cylinder was immersed in a lagged and well-stirred oil bath held within 0.05° of the desired temperature. The difference in temperature between the center of the cellulose and the oil was measured with a differential thermocouple. With the bath at 120°C dry nitrogen (10 ppm oxygen) was passed through the cellulose until thermal stability (cellulose about 0.2° hotter than the oil) indicated that almost all moisture had been removed. Then the oil bath was adjusted to the desired ambient temperature and dry air was substituted for the nitrogen. The consequent rise in central temperature measured by the thermocouple was recorded on a strip chart recorder and checked by manual reading of a potentiometer. If the rise attained 100°C, slow thermal explosion (ignition) was in progress and further reaction was quenched by replacing the air flow with nitrogen.

For viscose rayon log–log plots of central temperature rise against time for various ambient temperatures from 148° to 167°C were curves that rose rapidly to peaks, not over 5°, within 3 hours, fell to minima and then rose slowly but remained below 10° even after 500 hours. The curve for ambient 167° began to decline a second time after somewhat less than 500 hours. The curves for ambients 170° to 180°C, after the peak within 3 hours, either declined to minima or rose less rapidly for a time and then rapidly accelerated into slow thermal explosion, which was quenched at 100°C central temperature rise. Curves for ambients 184° and 188°C showed no retardation within 3 hours but accelerated steadily to slow thermal explosion. At ambient 188°C slow thermal explosion was reached in about 3 hours whereas at ambient 170°C somewhat more than 100 hours were required. Results with filter paper and cotton wool were similar except that they were less reactive than viscose rayon in that the peaks within 3 hours were smaller and the time to reach slow thermal explosion was longer. But the critical ambient temperature necessary for slow thermal explosion to be attained remained the same, about 170°C, for filter paper and cotton wool as for viscose rayon.

The results suggest that two different exothermic chemical reactions are involved. The first probably is reaction of cellulose with oxygen at a rate that diminishes with time. It produced the thermally unstable state at 184° and 188°C that led to ignition in these experiments. But at lower ambient temperatures the retardation following the initial upsurge showed that the first reaction had spent its force before thermal instability set in. When the logarithm of time delay before ignition was plotted against the ambient temperature two straight lines intersecting at 182°C were obtained to indicate two different reactions. (Under other conditions of geometry and bulk density of cellulose the transition between the two reactions might be at temperatures other than 182°C).

Cellulose is known to degrade slowly at high temperatures. The second reaction, which accounts for the ultimate ignition at ambients 171° to 180°C in these experiments, probably is exothermic reaction of oxygen with pyrolysis products of cellulose degradation at a faster rate than with the original cellulose. Since a strong odor of caramel was given off when slow thermal explosion was attained it is suggested that there is a chain cleavage producing pyrolyzed glucose units (perhaps levoglucosan), which would then react with oxygen more rapidly than the original cellulose.

In wood the cellulose probably is subject to a similar accelerating rate of oxidation but the effect may well be masked during the early stages of reaction by oxidation of extractives and possibly of lignin. Pure cellulose requires a higher temperature for ignition than would pulp or wood flour.

C. Detection of Fires

O'Dogerty, M. J. (Joint Fire Research Organization, Borehamwood, England) "The Detection of Fires by Smoke. Part 2. Slowly Developing Wood Crib Fires," *Joint Fire Research Organization Fire Research Note No. 793* (November 1969)

Section: C
Subjects: Detector; Fire; Smoke; Optical; Ionisation; Investigation; Specification

Authors' Abstract

Measurements have been made, at ceiling level, of the optical density per metre of smoke from slowly developing wood crib fires. Results are given for ceiling heights from 2.4 m to 7.0 m (8 ft to 23 ft) above the fire, and for horizontal distances up to 9.8 m (32 ft) across the ceiling. In these experiments, the change in potential across the open chamber of an ionisation smoke detector, and the output signal from an optical scattering smoke detector were also continuously recorded. In addition, the response times of some proprietary smoke detectors were measured.

The significance of the results in relation to a suitable sensitivity test for smoke detectors is discussed.

Stojsavljevic, D. "Early Discovery of Spontaneous Heatings in Coal Mines through the Determination of Traces of the Lower Hydrocarbons," *Sigurnost u Rudnicima* (Yugoslavia) 4 (2), 47–52 (1969). In Serbo-Croatian.

Section: C
Subjects: Discovery of spontaneous heating; Hydrocarbons; Spontaneous heating

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The chief instruments used for the quantitative analysis of mine gases are reviewed. From an examination of the results of the author's own work on the subject it is concluded that the presence in mine gas of unsaturated hydrocarbons, as well as their concentrations, is an indication of the intensity of the chemical processes causing the heating. The first indication of the beginning of this process is the detection of even the slightest trace of ethylene. The determination of these components is only possible by means of gas chromatographic analysis.

D. Propagation of Fires

Baldwin, R. and Thomas, P. H. (Joint Fire Research Organization, Borehamwood, England) "The Spread of Fire in Buildings—Effect of Varying Standards of Fire Cover," *Joint Fire Research Organization Fire Research Note No. 789* (October 1969)

Section: D
Subjects: Attendance; Brigade; Fire cover; Fire spread; Fire statistics

Authors' Abstract

The statistics of fires attended by the fire brigades are used to examine the effect of different standards of fire cover and attendance time on the chance of a fire spreading beyond the room of its origin. The analysis has been performed for several different occupancies and reveals no significant trend for fires to spread in multistorey buildings as the attendance time gets longer.

As a result of comparing different risks it appears that in most occupancies, the system of varying standards of cover compensates for different risks of spread, so that high risks have the same chance of confinement as low risks. However, there are one or two exceptions, notably in the manufacturing industries, where some classes of building have a much higher chance than average of fires spreading beyond the room of origin, and data for these buildings require further examination.

Heselden, A. J. M. and Theobald, C. R. (Joint Fire Research Organization, Borehamwood, England) "The Prevention of Fire Spread in Buildings by Roof Vents and Water Curtains. Part 1. Fire Experiments," *Joint Fire Research Organization Fire Research Note 791* (November 1969)

Section: D
Subjects: Building; Fire spread; Roof; Smoke; Vents; Water curtains

Authors' Abstract

The rapid horizontal spread of fire in a building compartment is largely the result of the deflection of flames by the ceiling and the flow over large distances of hot gases under it.

Opening enough holes in the ceiling should therefore reduce this rate of spread, though the areas of vention required will be much larger than required to reduce smoke logging, but no amount of venting can necessarily stop the fire if it can spread unaided by the ceiling. Such spread could be controlled, where necessary, by water. Water curtains or sprinklers—without vents—control fires before they become too large. In principle the combined use of vents and water could prevent the spread of very large fires.

E. Suppression of Fires

Baltaitis, V. Ya., Belik, I. P., and Zrelyi, N. D. "Extinguishing Underground Fires Accompanying Explosions of Methane," *Bezopas. Truda Prom.* **13** (7) 12–16 (July 1969). In Russian.

Section: E
Subjects: Explosions; Extinguishment; Firedamp; Fires, underground; Methane; Mine fires; Underground fires

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The article outlines in detail the measures taken in extinguishing the fire which occurred in the mine of the Luganskugol' region. The information is provided with a view of assisting people who might be engaged in fighting mine fires. The authors describe remote air sampling, listening-in to explosions, measuring methane concentration, determining shock wave pressure in places of erection of stoppings, remote filling with nitrogen, etc. and end with conclusions and recommendations.

Baltaitis, V. Ya., Kushnarev, A. M., Markovich, Yu. M., and Petrov, P. P. "Investigation of Conditions for Using Active Methods of Extinguishing an Underground Fire," *Ugol' Ukr.* **13** (7), 33–34 (July 1969). In Russian.

Section: E
Subjects: Active extinguishment; Extinguishment; Fires, underground; Mine fires; Underground fires

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The dependence of the specific mass flow rate of combustion on the time, under conditions of a ventilated working, is calculated. It is shown that when a fire reaches a certain heat output active extinction becomes ineffective. Formulae are worked out to determine the expediency of using active methods of extinction.

Komamiya, K. "The Quenching Ability of Flame Arresters for *n*-Hexane," *Rep. Res. Inst. Ind. Saf.* (Japan) **17** (4), 5 p. (March 1969). In Japanese.

Section: E
Subjects: Arresters, flame; Hexane; Flame arresters; Quenching

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To prevent fires and gas explosions in the chemical industry, flame arresters are mounted on oil tanks or similar installations, but their effectiveness has not been firmly established by experiment. The author has investigated these arresters using *n*-hexane-air mixtures. Their concentration was determined with an interferometer having a gas chamber 48 mm long, taking a value of 1.002032 for the refractive index of hexane. The wires in the arresters were of stainless steel with a nominal size of S.W.G. 26 and a mesh of 16. The direction of flame propagation was vertical. The quenching ability of the arresters is shown in graphs.

Riccitiello, J. A., Gilwee, W. J., and Fish, R. "Fire-Retardant Foams to Suppress Fuel Fires," *NASA Tech. Briefs, ASSE Jnl.* **14** (2), 26 (February 1969)

Section: E
Subjects: Fire retardant; Fires, fuel; Foams; Fuel fires; Polyurethane; Retardant foams; Suppression

Abstract by Safety in Mines Research Establishment, England.
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Heat insulating and fire retarding and suppressing material (semi rigid or rigid polyurethane foam) has uniformly dispersed in it a large amount of halogenated polymer to split off hydrogen halide upon heating and charring of polyurethane.

Stratta, J. J. (Union Carbide Corporation) **and Livingston, W. L.** (Factory Mutual Research Corporation) "Ablative Fluids in the Fire Environment," *Fire Technology* **5**, 181–192 (1969)

Section: E
Subjects: Ablation; "Ablative water"; Fluids

Reviewed by J. E. Malcolm

The efficacy of "ablative" water films to control fires was investigated by the authors. In this study, ablative water is characterized by a gel consisting of water and ionized polymer chains, which have the property of building up ablative coatings on exposed solid fuel surfaces, and are sufficiently fluid that application to burning fuel surfaces can be made. The authors omit any discussion of the composition of the ablative water films that might determine the thermal stability of the film (or ablator) and they do not specify the gelling agent used, nor its concentration in water dispersion to form the ablator.

Introductory discussions are presented concerning the mechanisms of ablative protection of exposed fuel elements in fire environments and the rheology of gels.

Three configurations of fuel and fire-fighting agent interaction are defined as follows: Case A is the configuration involving the interaction in a horizontal fuel-fire interface. Case B involves a vertical fuel-fire interface, and Case C concerns the fuel and fire extinguishing medium only. The extents of fuel-agent interactions in Case C are shown in Fig. 1 for plain water and ablative water. Figure 1 shows (presumably at room temperature, Reviewer's Note) that much more ablative water than plain water is retained after application in a 12 ft stack of wood pallets, each measuring $48 \times 48 \times 4$ in. in depth.

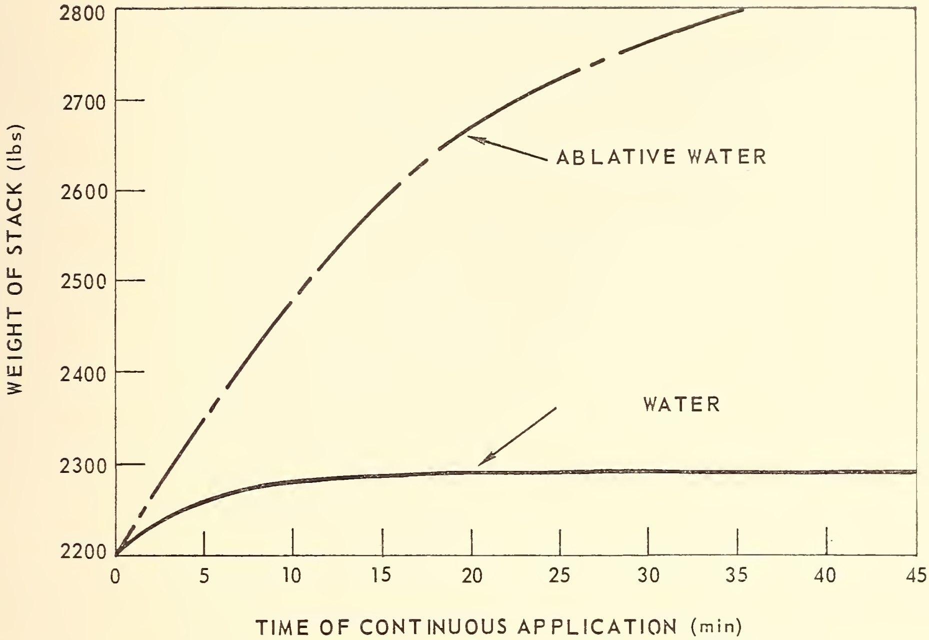

FIG. 1. Plain water vs. ablative water applied at 0.20 gpm/ft² of plan area at top of 12-ft stack of 48-in. by 48-in. pallets.

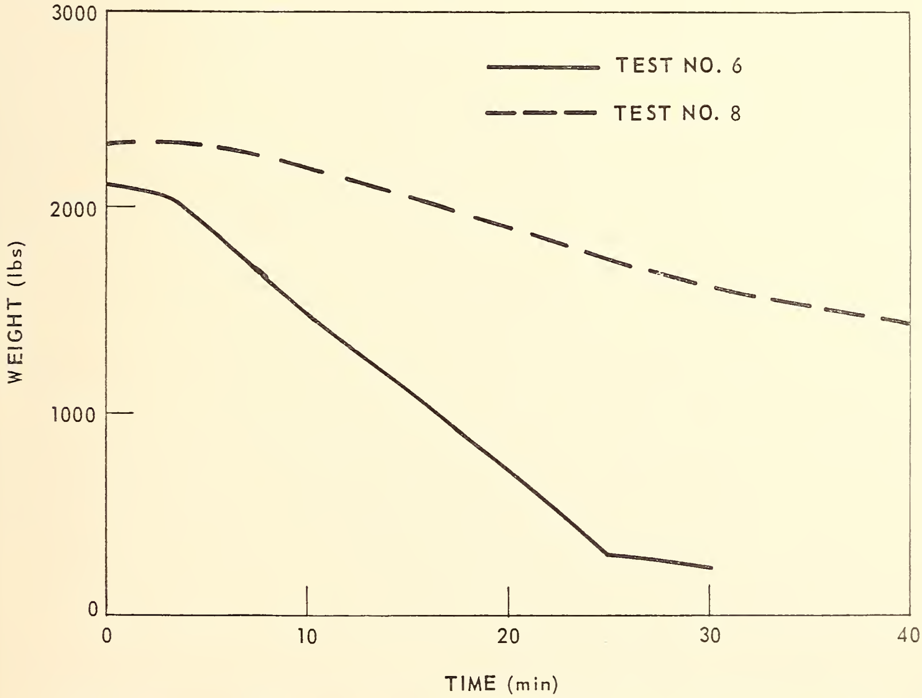

FIG. 2. Comparison of fuel consumption in Test No. 6 (water) and Test No. 8 (gel).

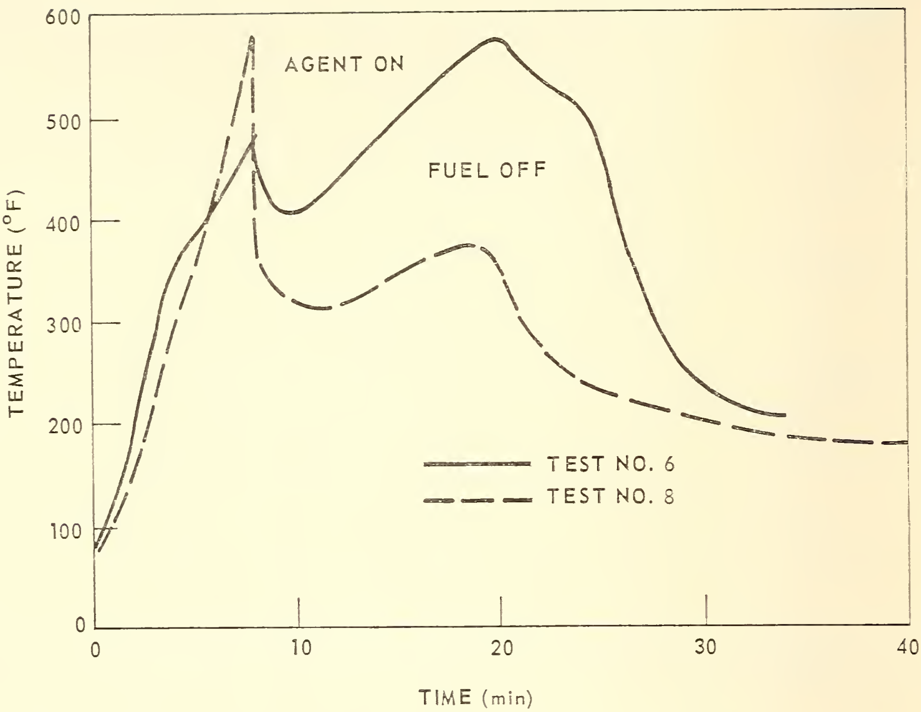

FIG. 3. Temperature comparisons in Test No. 6 (water) and Test No. 8 (gel).

For the test fires, the Case A situation was selected, in which supported wood pallets (25 pallets, 48×48×4 in. in depth, stacked to a height of 12 ft)* were exposed within a burning gasoline spray fire environment to simulate the burning of "hypothetical" adjacent stacks. A spray-rate corresponding to the maximum free-burn heat release was used for 18.5 min so as to consume most of the pallet pile, without pile collapse. In the test fires reported, after a fire preburn of 5.5 min in the configuration described above, the agent (plain water or ablative water) was delivered vertically and uniformally to the top of the pile at approximately 0.15 gal/min/sq ft area.

The plots of Figs. 2 and 3 summarize the results obtained from fire tests Numbers 6 and 8. Note that the gasoline fuel spray was terminated at about the midtime in the overall test time reported.

The authors compare, in the plot of Fig. 4, starting at 10 min from time of ignition of the test fire, test-fire temperature as a function of solid fuel remaining in the fire-test configuration using plain water and ablative water.** They report also that the ablative water penetration in fuel reaches a depth of 7.5 in. in 30 minutes for a

* The exact support configuration giving the height of 12 ft was not discussed in this paper—Reviewer's Note.

** Methods for determining with continuous readout the solid fuel mass residue, on a dry basis, as the test fire and agent application progress are not discussed. However, the authors point out that the fuel weights reported in these test fires are approximate since some agent (water or ablative water) weight is included.

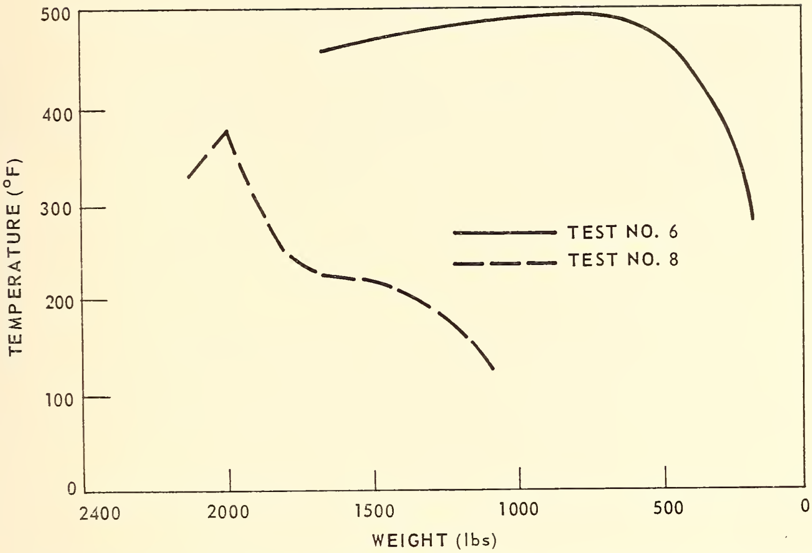

FIG. 4. Comparison of temperature vs weight for Test No. 6 (water) and Test No. 8 (gel), starting 10 min after ignition.

0.15 gal/min/sq ft application rate, and that ablative water acts to seal, confine, and sequester flaming debris which otherwise would help spread or support burning.

The authors conclude that further test and study will be required to explain the effectiveness of ablative liquids in "high challenge" fires, such as the pallet-fire configuration used in the fire tests reported.

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G. Combustion Engineering

Affens, W. A. (Naval Research Laboratory, Washington, D. C.) "Flammability Properties of Hydrocarbon Solutions in Air," *Paper presented before the Division of Petroleum Chemistry, Inc., American Chemical Society, Chicago, Illinois,* September 11–15 (1967)

Section: G
Subjects: Flammability; Hydrocarbons

Reviewed by J. M. Singer

Lower and upper flammability limits, heats of combustion, stoichiometric concentrations of vapor-air above liquids, flash points, and flammability index are defined for multicomponent liquid fuels. Mathematical expressions based essentially on the principles of Le Chatelier, Raoult, and Dalton are given for numerical prediction of these flammable characteristics.

The equations, which clearly indicate how small amounts of highly volatile contaminants in a relatively nonflammable fuel may make it flammable are summarized below.

1. Flammability limits of vapor-air mixtures:

   a. For the lower flammability limits (L_M):

$$1/L_M \sum_i (N_i'/L_i) = N_A'/L_A + N_B'/L_B + \cdots$$

   b. For the upper flammability limit (U_M):

$$1/U_M = \sum_i (N_i'/U_i) = N_A'/U_A + N_B'/U_B + \cdots$$

2. Stoichiometric concentrations of vapor-air mixtures (C_{SM}):

$$1/C_{SM} = \sum_i (N_i'/C_{Si}) = N_A'/C_{SA} + N_B'/C_{SB} + \cdots$$

3. Molar heat of combustion of vapor-air mixtures (ΔH_m):

$$\Delta H_m N = \sum_i (N_i' \Delta H_{mi}) = N_A' \Delta H_{mA} + N_B' \Delta H_{mB} + \cdots$$

4. Vapor mixtures containing two fuel components:

$$X_B' = L_B - (L_B/L_A) X_A'$$

$$1/LM = (1/L_B - 1/L_A) N_B' + 1/L_A$$

5. Flammability index of vapor-air mixtures (E_t, E_M):

$$E_t = X_t'/L_t$$

$$E_M = \sum_i E_i = E_A + E_B + \cdots = 1$$

6. Effect of temperature on flammability limits of vapor-air mixtures:

$$L_{Mt}/L_M = (1.02 - 0.000721t)$$

$$U_{Mt}/U_M = (1.02 - 0.000721t)$$

7. Vapor composition above the liquid solution:

$$N_i' = N_i p_i / \sum_i (N_i p_i)$$

8. Flammability limits of liquid solutions (L_M):

$$1/L_M = \sum_i (N_i p_i / L_i) / \sum_i (N_i p_i)$$

9. Flammability index of liquid solutions (E_{Mt}):

$$E_{Mt} = \sum_i (N_i E_{it}^0)$$

and

$$E_{Mt} = E_{At}^0 - (E_{At}^0 - E_{Bt}^0) N_B \text{ for a binary solution}$$

10. Flash points (t_L and t_U):

a. $\sum_i (N_i p_{it}/L_i) + 7.21 \times 10^{-6} t_{LM} - 0.0102 = 0$

b. $N_A p_{At}/L_A + N_B p_{BT}/L_B + 7.21 \times 10^{-6} t_{LM} - 0.0102 = 0$ for a binary solution.

c. $\log_{10} p_{it} = b_i + M_i/(t_{LM} + C)$

d. $\sum_i \{[(1642 - T_{Li}')N_i/(1642 - T_{LM}')] \times 10 M_i (T_{Li}' - T_{LM}')/T_{Li}' T_{LM}'\} = 1,$

where $T' = t + 230$

Symbols:

X'	actual vapor concentration, percent by volume
L	volume concentration at lower flammability limit, percent by volume
i	property of a general component
A, B	etc., property of a specific component
N'	mole fraction of a given fuel component in the total fuel vapor (air-free basis)
M	overall property of the mixture
ΔH	molar heat of combustion
C_S	stoichiometric concentration, percent by volume
E_t	flammability index, decimal ratio of X_t'/L_t
t	temperature
p	vapor pressure, atmospheres
p_i	vapor pressure of the pure liquid component i, atmospheres
N_i	liquid concentration, mole fraction
$\sum_i (N_i p_i)$	total vapor pressure, atmospheres
E_{it}^0	flammability index of vapors above a pure liquid component $= 100 p_{it}/L_{it}$
t_L and t_U	lower and upper flashpoint temperature (where vapor pressure of the fuel is equivalent to the concentration at the lower and upper flammability limits respectively)
p_{it}	vapor pressure at the flashpoint temperature
L_{it}	lower flammability limit at the flashpoint temperature
b_i, M_i	constants varying for each hydrocarbon

"**Burning at Internal Surfaces of Coal Particles,**" *Coal Research CSIRO* (37) 6–7 (May 1969)

Section: G
Subjects: Coal; Internal burning; Particles; Surface burning

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Electron microscope observations have shown that the porous particles formed during combustion have external openings about a thousand times the size of oxygen molecules which can, therefore, readily penetrate into the interior. Contrary to the view held until recently, in the pulverised bituminous coal examined, burning thus occurs at the internal as well as the external surfaces of the particles.

Burge, S. J. and Tipper, C. F. H. (Donnan Laboratories, The University, Liverpool, England) "The Burning of Polymers," *Combustion and Flame* 13 (5), 495–505 (1969)

Section: G.
Subjects: Burning; Flame structure; Polymers

Reviewed by G. A. Agoston

This is a report of an experimental investigation of the candlelike burning in air at atmospheric pressure of rods (1 in. and $\frac{1}{2}$ in. diameter) of low and high density polyethylene and of polymethylmethacrylate. The aim of the study was to elucidate the steps involved in going from the solid polymer to the combustion products.

The low density polyethylene contained 27 methyl groups per 1000 carbon atoms; the high density polymer contained essentially none. For purposes of comparison the study included observations of the burning of pure liquid *n*-eicosane (mp 37°C) in air and of the burning of low density polyethylene in a series of O_2–N_2 and O_2–He mixtures. Loose fitting Pyrex mantles were used to control the flame height and width of the polymers and to prevent dribbling. An outer shield and a distributor assured the uniform upward passage of metered air or gas mixture.

When a stable flame was established, the top end of the low density polyethylene rod was molten to a depth of 2 cm, the melt temperature was about 400°C, and no bubbling was apparent. The melt of the high density polyethylene was very viscous and not as deep. The polymethylmethacrylate rod ignited more easily and burned more quickly. The surface became conical moistened by a thin bubbling fluid layer; the surface developed a tarry appearance. When the oxygen content of the ambient gas was increased, the temperature of the melt of the low density polyethylene increased markedly and at 60% oxygen the melt began to bubble violently. When He was substituted for N_2, the melt temperature increased similarly with increase in oxygen content, and bubbling started at 40% oxygen. The temperature at the liquid surface of the *n*-eicosane was about 325°C and no bubbling was visible.

The flames of the polymers and *n*-eicosane burning in air had very much the same appearance. The flames consisted of a cylindrical blue zone (3 to 4 mm deep) on top of which was a smoky yellow cone about 3 cm high. Between the melt surface and the flame was a thin ($\leq$1 mm) nonluminous gap. On increasing the oxygen content of the atmosphere, the luminous zone of the low density polyethylene flame became more intense until finally the lower blue region disappeared leaving a bright whitish cone and an increased gap. Above 60% oxygen a blue region appeared around the base of the cone and the flame became very smoky. When helium was substituted for nitrogen, a stable flame was difficult to obtain. At 20% O_2–80% He, the nonluminous gap was larger and the flame consisted of an unstable blue cone ($\sim$1 cm high) capped by a yellow peak ($\sim$0.5 cm high). At 40% O_2–60% He, the flame was mainly luminous and very smoky.

Temperature profiles in the flame were obtained with the use of a fine quartz-sheathed platinum/platinum-rhodium thermocouple inserted axially from above and from below (passing through a central hole in the polymer) and radially from the side. For all the polymer flames these profiles are very much the same, rising sharply to a maximum of about 700°C at 1.5 to 2.5 cm above the melt. The maximum flame temperatures with low density polyethylene were all about the same irrespective of the various O_2–N_2 and O_2–He ambient gas mixtures used. In the case of burning *n*-eicosane, the profiles were similar, but the temperatures were lower; the maximum temperature was 620°C.

Flame gases were sampled by means of a small quartz tube at various axial and radial positions. Gas chromatographic procedures were employed to identify and determine nitrogen, oxygen, methane, carbon monoxide, carbon dioxide, ethylene, ethane, propene, propane, asetylene, 1-butene, *n*-butane, methylmethacrylate, alcohols, ketones, water, and higher aldehydes. Formaldehyde was determined colorimetrically and separate tests were conducted for peroxides.

Axial composition profiles are presented for low density polyethylene burning in air and in a 40% O_2–60% N_2 mixture and for high density polyethylene, polymethylmethacrylate and *n*-eicosane burning in air. Radial composition profiles are presented for low density polyethylene flames in air at both 0.1 cm and 0.5 cm above the melt surface and in a 40% O_2–60% N_2 mixture at 0.1 cm above the surface, and for high density polyethylene and polymethylmethacrylate flames in air at 0.1 cm above the surface. In each instance a profile of oxygen consumed is also given.

The axial composition traverse for the low density polyethylene air flame shows that very close to the melt surface at least 70% of the gas mixture consisted of N_2. The rest was O_2 (<2%), CO (5%), CO_2 (10%), H_2O (5%), and low molecular weight hydrocarbons (<10%). Traces of formaldehyde and peroxides were found only near the flame's edge and no other oxygenated organic compounds were detected. Upwards from the surface the axial concentrations of N_2, O_2, CO_2, and H_2O (especially) increased, the concentrations of CO and C_2H_2 rose and then fell to zero, and the concentrations of the remaining hydrocarbon constituents decreased. The concentrations of N_2, O_2, CO_2, and H_2O decreased radially toward the center and the concentrations of CO and hydrocarbons increased. For both 40% O_2–60% N_2 and

40% O_2–60% He, the trends were as follows: the amounts of oxygen at the base of the flame were less than for polymer burning in air, the amount of oxygen consumed was about double, the N_2 or He concentrations were reduced 25%, and the other components were about double. The axial and radial concentration patterns for 40% O_2–60% N_2, however, were similar to those for air.

Axial composition profiles for the high density polyethylene air flame show greater concentrations of hydrocarbons (except CH_4), O_2 and CO than with low density polyethylene and slightly smaller concentrations for N_2 and H_2O. The oxygen concentration fell to a minimum at 1.5 cm above the melt. In the polymethylmethacrylate flame just above the melt, the oxygen concentration was again very small and the methylmethacrylate was the major organic constituent. Upwards from the surface the axial concentrations of N_2, CO_2, and H_2O increased and the organic components decreased, with methylmethacrylate falling very sharply. The radial profiles show maxima at the center for CO_2, H_2O, and consumed O_2.

The axial composition profiles for the *n*-eicosane flame resemble those for high density polyethylene, though the amount of CH_4 was greater and that of CO less. Appreciable amounts of *n*-eicosane vapor seemed to be present close to the surface. Liquid samples taken close to the surface contained constituents having the $>C=O$ group. When mercury diethyl was present in the liquid, orange mercuric oxide developed in the surface layer of the liquid.

The authors propose that the following steps characterize the burning of polymers: Air or ambient gas is drawn into the nonluminous gap, flowing radially toward the center. Reactions occur principally in the surface layers of the polymers (i.e., thermal degradation, oxidative degradation, and oxidation to carbon oxides and water) providing a very fuel-rich mixture which burns essentially as a diffusion flame.

The following observations and considerations give support to their conception:

The concentration of oxygen at the surface of the melt is very small.

Residence-time estimates show that little oxidation and thermal cracking of gases can occur in the nonluminous gap. The rapid decrease in concentration of the hydrocarbons in the blue zone was probably due mainly to oxidative cracking.

The radial traverses in the nonluminous gap show a decrease in concentration of O_2, CO_2, and H_2O toward the center and a corresponding rise in concentrations of CO and hydrocarbons. The reverse trend noted for polymethylmethacrylate seems to have been due to the shielding by the mantle edge of the lower half of the conical burning surface.

Doubling the oxygen content did not cause the oxygen content in the flame to rise and the flame temperature to increase, but it did cause the temperature of the liquid melt to increase. The flame temperatures of the polymers were essentially the same, suggesting similar burning mixtures.

Surface reactions are indicated by the formation of mercuric oxide and the $>C=O$ group in the top layer of *n*-eicosane and of the tarry substance on the polymethylmethacrylate tip.

Relatively large amounts of methylmethacrylate vapor were formed, undoubtedly by thermal degradation in the polymer surface.

The amounts of CH_4 found was greatest for *n*-eicosane, less for low density polyethylene, and least for high density polyethylene which corresponds in order to the number of methyl groups per 1000 carbon atoms. This is in agreement with certain rapid surface reactions that are expected to occur under such conditions. Ethylene is a possible oxidative degradation product of long chain alkyl or polymeric radicals, and acetylene of higher olefin intermediates. Ketones and higher aldehydes, being readily oxidized, were not detected; CO and CO_2 were probably formed during aldehyde oxidation.

Dmitriev, B. M., Kochetov, O. A., Ulybin, V. B., and Shteinberg, A. S. (Leningrad) "Measurement of the Total Heat of High-Temperature Gasification of Polymers," *Physics of Combustion and Explosion* 5, 26–30 (1969).* In Russian.

Section: G
Subjects: Gasification; Heat of gasification; Polymers; Pyrolysis

Authors' Summary—Translated by L. Holtschlag

Data are obtained on the total gasification heat (Q) from experiments in the linear pyrolysis of polymethyl methacrylate and paraformaldehyde. A block calorimeter is heated to a given temperature, a specimen is applied to the heated surface, and the Q is determined from the change in temperature field in the block during the stages of pyrolysis and thermal relaxation, knowing the effective heat capacity of the block and the weight of the specimen. The computational formula for determination of Q is obtained from the solution of two problems of nonstationary thermoconductivity of the block corresponding to the two above-mentioned states. The results are given in diagram and graph form. Processing of the results shows that the regular mode (linear section) sets in comparatively earlier in the middle section of the block than at other points. The values of Q, accurate to within 8% to 10%, are 380 cal/g for PMM and 440 cal/g for paraformaldehyde.

Tkachenko, E. V., Ulybin, V. B., Shteinberg, A. S. (Leningrad) "Linear Pyrolysis of Polymethyl Methacrylate," *Physics of Combustion and Explosion* 5, 16–26 (1969).** In Russian.

Section: G
Subjects: Methylmethacrylate; Polymethyl methacrylate; Pyrolysis

Authors' Summary—Translated by L. Holtschlag

A series of experiments in the linear pyrolysis of polymethyl methacrylate was carried out in order to verify Cantrell's model of pyrolysis and a method of approxi-

* Complete English Translation, Applied Physics Laboratory, The Johns Hopkins University Translation No. 2426.

** Complete English Translation, Applied Physics Laboratory, The Johns Hopkins University Translation No. 2424.

mate determination of the surface temperature developed by the authors on the basis of Schultz and Dekker's model of linear pyrolysis. The experimental arrangement was essentially that of Barsh and Anderson; the variable parameters were the contact pressure ($W=5.46$, 9.89, 12.32, 16.55 N) and the diameter of the specimen ($b=0.6$, 0.8, 1.0, 1.2×10^{-2} m). Most of the experiments were carried out with a stainless steel heating plate in a nitrogen atmosphere, except for experiments at the maximum pyrolysis rates, when a niobium plate was used, because of its high MP (2,500°C). The results are given in the form of graphs: (1) dependence of the linear decomposition rate on the diameter of the specimen and the contact pressure, the effect of these parameters being faster decomposition at the higher plate temperatures as a result of increasing thickness of the gas film with increasing linear pyrolysis rate U; (2) calculation of the surface temperature T_s of PMM, which at high linear decomposition rates is either constant or weakly dependent on the heat flux to the surface and the linear pyrolysis rate; (3) determination of the dependence of T_s on U in pyrolysis of linear and cross-linked PMM, yielding the affective activation energy and rate constants.

Talantov, A. V., Ermolaev, V. M., Zotin, V. K., and Petrov, E. A. (Kazan) "Study of the Relations for Combustion Processes in a Turbulent Flow of Homogeneous Mixture," *Physics of Combustion and Explosion* 5, 106–114 (1969). In Russian.

Section: G
Subjects: Combustion processes; Turbulence; Turbulent combustion

Authors' Summary—Translated by L. Holtschlag

Flame propagation rates, burning time, and combustion zone length are studied on the basis of a review of the literature data, especially those of the authors, for the "surface" burning mechanism in a turbulent flow of a homogeneous mixture. Particular attention is paid to the effect of pressure and temperature on the flame speed and burning time. Also discussed is the applicability of experimental results obtained in an open flow to combustion chambers, which is considered feasible, the error not exceeding 5%. The results have been used in particular for the dimensioning of ramjet combustion chambers, taking into account the flight altitude and speed.

Shteinberg, A. S. and Ulybin, V. B. (Leningrad) "On Two Modes of Linear Pyrolysis of Condensed Materials," *Physics of Combustion and Explosion* 5, 31–41 (1969). In Russian.

Section: G
Subjects: Condensed materials; Linear Pyrolysis; Pyrolysis

Authors' Summary—Translated by L. Holtschlag

The aim of this theoretical study is to clarify the characteristics of linear pyrolysis when the heat lost to the ambient medium is appreciable and to determine a criterion for transition from this mode to one in which the heat transfer can be neglected. Three cases are examined: thermoneutral reaction $Q=0$; reaction with a small thermal effect (much less than unity); and reaction with a large thermal effect (much greater than unity). An analysis is made of the expression for the linear pyrolysis rate. It is found that with decreasing surface temperature as the rate of linear decomposition falls off, pyrolysis shifts from the inner diffusion region to the outer kinetic region, characteristic of which is coincidence between the macroscopic kinetics and the true kinetics of the decomposition reaction. A formula for linear pyrolysis with allowance for finite sample length is also given.

H. Chemical Aspects of Fires

"**Fire Hazards Computed from Thermodynamics,**" *Chemical and Engineering News* (November 24, 1969)

Section: H
Subjects: Fire hazards; Thermodynamics

Reviewed by W. E. Wilson

A method has been developed for predicting the explosion hazard of new chemical compounds. Dr. Daniel R. Stull, Dow Chemical Company, Midland, Michigan, bases the predictive technique on the thermodynamics of combustion and decomposition. The chemical composition and heat of formation of the compound is required as input. A slightly modified program for the calculation of chemical equilibria then makes calculations for the two states. For combustion the computer first balances the stoichiometry for zero oxygen balance—carbon to carbon dioxide, hydrogen to water, halogens to the hydrohalogen acid, and sulfur to sulfur dioxide. Using the amount of air needed to supply the required oxygen, the computer calculates the combustion products at flame temperature, the heat released, the total number of moles, and the temperature and pressure for a constant volume combustion. A similar process is performed for decomposition to the most stable products in the absence of added oxygen. The difference between the heat of combustion (ΔH_c) and the heat of detonation (ΔH_d) was used as an indicator of each compound's sensitivity. Similar comparisons were made using the difference between the combustion and detonation temperature and pressure.

These parameters were compared to the degree of hazard predicted by the presently used rating systems—The National Fire Protection Association's (NFPA) fire code rating and drop-weight tests. The results show that materials with a National Fire Code rating of 4 (the most highly explosive group) lie mainly along the baseline when $\Delta H_c - \Delta H_d$ (vertical ordinate) is plotted against ΔH_d (horizontal ordinate), when $T_c - T_d$ is plotted against T_d, or when $P_c - P_d$ is plotted against P_d. In addition, the lower third of the temperature chart, for example, contains hazardous explosives or materials with an NFPA rating of 3 or 4 (shock-sensitive explosive materials). The middle third of the chart (where $T_c - T_d$ is greater than 1000°K but less than 2000°K) contains materials that are explosive but are mixed in their degree of shock sensitivity. The upper third of the chart (above 2000°K) contains materials that are almost entirely stable and which carry an NFPA rating of 0.

Thus, there is a more or less gradual progression from the most hazardous materials in the lower right corner to the "safe" materials in the upper left. By dividing the imaginary line through most of the points into five segments, Dr. Stull can assign rating numbers to his results, similar to the numbers (0–4) carried by NFPA-rated materials. These "Stull numbers" agree with the NFPA ratings in 143 of the possible 150 comparisons (heat release, temperature, and pressure plots for each of the 50 compounds studied).

Lipska, Anne E. (Naval Radiological Defense Laboratory, San Francisco, California) "The Synergistic Effect of Benzhydrylation-Iodination on the Flammability of Alpha Cellulose," *NRDL TR-69, Office of Civil Defense Task Order DAHC20-67-C-0149, Work Unit 2542A* (May 1969)

Section: H
Subjects: Alpha cellulose; Benzhydrylation; Cellulose degradation; Flammability; Iodination; Pyrolysis

Author's Abstract

Cellulose samples were subjected to various degrees of iodination, benzhydrylation and benzhydrylation followed by iodination. The effect of these treatments on crystallinity, rate of thermal degradation, char production and pyrolysis products was investigated. Results indicated that in general the crystallinity index varies inversely with the percent of substitution, rate of weight loss, and amount of residual char. Although the rates of weight loss of the substituted samples increased from 0.3%/min to as high as 108%/min depending on the type and percent of substitution, the overall weight loss pattern of the treated cellulose was similar to that of the untreated samples. Of the three types of retardants tried, iodine was the best flame retardant in that the residual char increased by a much larger factor for a given increase in rate. The addition of benzhydryl to the iodinated sample seemed to decrease rather than increase the char producing ability. All three treatments

drastically reduce the number of degradation products of molecular weights lower than 150; untreated cellulose gave 59 component whereas the substituted cellulose led to five major compounds; water, acetic acid, furfural, 5 methyl-2-furfuraldehyde, and 1,5 anhydro-2,3 doxy-beta-*D*-pent-2-eno-furanose. Of these, water and the furnaose derivative were the major components.

Rasbash, D. J. (Joint Fire Research Organization, Borehamwood, England) "Fire Protection Engineering with Particular Reference to Chemical Engineering," *Joint Fire Research Organization Fire Research Note No. 787* (October 1969)

Section: H
Subjects: Chemical engineering; Explosions; Fire protection

FRAR Editorial Comment

This Fire Research Note provides a resume of four lectures that were to be given at the Chemical Engineering Department, University College, Swansea, November 6 and 7, 1969. A brief statement of the principles underlying fire processes and protection against fire and explosions is outlined.

Woolley, W. D. and Wadley, Ann, T. (Joint Fire Research Organization, Borehamwood, England) "Studies of Phosgene Production during the Thermal Decomposition of PVC in Air," *Joint Fire Research Organization Fire Research Note No. 776* (October 1969)

Section: H
Subjects: Gas chromatography; Phosgene; Plastics

Authors' Abstract

The production of phosgene during the thermal decomposition of both a commercial PVC and a relatively pure PVC polymer at temperatures between 250° and 500°C in air has been studied by gas chromatogaphy. Difficulties encountered with the general handling and analysis of phosgene are recorded. Phosgene has not been detected in any experiment and minimum detection limits have been determined by adding known amounts of phosgene to the system during the decompositions. By comparing the detection levels of phosgene with the yields of hydrogen chloride, phosgene is shown to make little contribution to the toxicity of the decomposition products. Some general recommendations are given for sampling fire gases for phosgene studies during large-scale tests.

I. Physical Aspects of Fires

Saito, Y. and Ishigaki, M. "Study of the Relation between Electrostatic Charge and Size of Inner Diameter of PVC Tubes," *Min. & Saf. Japan* **15** (6) 288–295 (1969). In Japanese.

Section: I
Subjects: Electrostatic charge; PVC; Tube diameter

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The experimental results obtained are as follows: When compressed air mixed with limestone dust flows in a PVC tube the polarity of the electrostatic charge is usually changed by the amount of limestone dust in the air and the current velocity of the air in the tube. When the limestone/air mixture ratio in the tube is 200–250 g/m^3 the electrostatic charge generated was found in these tests to be at a maximum. The higher the air velocity in the tubes the higher is the electrostatic charge generated on the surface of the tube. The electrostatic charge is not greatly affected by the maker's classification of the tube. Since the moisture content of mine air is relatively high and little dust is carried in the gas drainage hardly any electrostatic charge is generated on tubes in underground coal mines. There is scarcely any difference between the charges generated on PVC tubes and on polyethylene tubes.

Shkandinskii, K. G, and Filonenko, A. K. (Moscow) "The Problem of Flame Propagation Taking the Hydrodynamics and the Temperature Dependence of the Transport Coefficients into Account," *Physics of Combustion and Explosion* **5**, 80–84 (1969). In Russian.

Section: I
Subjects: Diffusion coefficients; Flame propagation; Hydrodynamics; Temperature dependence; Thermal conductivity; Transport coefficients

Authors' Summary—Translated by L. Holtschlag

The combustion rate is determined numerically on a computer in a broad range of parameters. A theoretical study is made of the effect of the temperature dependence of the thermal-conductivity and diffusion coefficients, the temperature dependence of the density, and the mean molecular weight on the combustion rate and the flame-front structure for a model of a continuous medium consisting of a hot gas mixture and combustion products. The temperature dependence of the diffusion and thermal-conductivity coefficients leads to smaller flame-front widths compared to the width calculated for constant coefficients at the burning temperature. The variability of the density also leads to a reduction in flame-front width, since the heat supplied for heat up is expended in heating gas which is denser than at the burning temperature. The absence of appreciable variations in the reaction zone explains the weak effect on the burning rate of the temperature dependence of the density and transport coefficients.

Zajac, L. J. and Oppenheim, A. K. (University of California, Berkeley, California) "Thermodynamic Computations for the Gasdynamic Analysis of Explosion Phenomena," *Combustion and Flame* **13** (5), 537–550 (1969)

Section: I
Subjects: Computation; Explosions; Gas dynamics; Hugoniot; Thermodynamics

Reviewed by F. A. Williams

This paper discusses in detail methods for approximating Hugoniot and Rankine–Hugoniot curves, shock, deflagration, detonation and expansion polars, and general isentropic flow parameters, for mixtures of real gases in chemical equilibrium.

It is argued that since the Hugoniot curve is a hyperbola in the pressure-volume plane for an ideal gas, it is reasonable in the case of a real reacting gas to calculate three points along the curve by an available accurate thermodynamic computer routine (the method of Brinkley, in particular, was adopted), and to pass a hyperbola through these three points for obtaining the rest of the Hugoniot curve. This kind of approach certainly saves space and time in computer calculations of complex gasdynamic flow fields, since in place of a long thermodynamic routine, merely a few fit constants need be stored, along with the brief routine for calculating the hyperbola. The only question is whether the results are accurate. Sample Hugoniot calculations for a hydrogen-oxygen mixture and dissociating oxygen reveal that in fact they are. The resulting curves generally agree very well with those obtained from a complete thermodynamic routine and depart somewhat from those obtained with the elementary perfect gas approximation. Thus, the method looks good, and the authors kindly volunteer to supply their computer program for it to anyone who would care to write to them at the University of California, Berkeley.

The "fit" philosophy is extended to isentropic flow calculations, wherein it is proposed that the usual assumption of a constant ratio of specific heats be replaced by the assumption that $(\partial h/\partial a^2)_s$ is constant, where h is enthalpy, a is sound speed and s is entropy. This particular replacement turns out to be not quite so successful as the preceding one, but still rather good.

The paper contains a table comparing a variety of numerical methods for evaluating Hugoniot curves on the basis of accurate thermodynamic data. The table includes a modification of Brinkley's method by the authors, in which they chose to search in the temperature rather than pressure coordinate, since curves for Hugoniot and state equations intersect more sharply in this new coordinate.

Readers concerned with calculating wave diagrams for inviscid reacting gases may wish to check over this paper to see if they can avail themselves of all this "tooling up" that has been done.

K. Physiological and Psychological Problems from Fires

Menn, S. J., Sinclair, R. D., and Welch, B. E. "Response of Normal Man to Graded Exercise in Progressive Elevations of CO_2. Report for 18 July to 24 September, 1967," *School of Aerospace Medicine, Brooks AFB Texas Report No. SAM-TR-68-116* (December 1968)

Section: K
Subjects: CO_2; Exercise; Man

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Trained volunteers performed steady-state moderate exercise (one-half of maximum CO_2) in 0, 8, 15, 21, and 30 mm Hg PI CO_2 for 30 minutes on a bicycle ergometer. At CO_2 levels of 8 and 15 mm Hg, no difficulty was encountered by the subjects. The higher levels of hypercapnia caused some respiratory symptoms of air-hunger and intercostal muscle pain, but were of mild enough degree to permit all subjects to complete the exercise. Incremental exercise up to workloads producing maximum V O_2 was also performed. The tolerance at maximum exercise in 21 mm Hg PI CO_2 resembled that at two-thirds workload in 30 mm Hg PI CO_2. V E during maximum exercise did not vary with the level of inspired CO_2, whereas at submaximal workloads, V E increased as PI CO_2 increased. At two-thirds and maximum workloads, V CO_2 during exercise fell progressively with increasing PI CO_2. The ineffective CO_2 removal is explained by the decreased alveolar-inspired CO_2 gradient with increasing PI CO_2. Inadequate elimination of CO_2 caused respiratory acidosis to be superimposed on the metabolic acidosis normally present during exercise.

Stark, G. W. V. (Joint Fire Research Organization, Borehamwood, England) "Toxic Gases from PVC in Household Fires," *Rubber and Plastics Age* **50**, 283–284 (April 1969)

Section: K
Subjects: Household fires; PVC; Toxic gases

Reviewed by A. Bidzinski

This paper deals with the effect of the addition of PVC to cellulosic fire loads on the toxic gases produced in small-scale laboratory fires. The principal toxic gas evolved in cellulosic fires is carbon monoxide. However, since it has been shown, that for a wide range of conditions, the chloride content of burning PVC is almost quantitatively released as hydrogen chloride, the effort has been made to determine the patterns of evolution of carbon monoxide and hydrogen chloride in fires involving both PVC and wood.

The tests were performed in 0.9 m cubic chamber with variable size vent. A crib of wood fibre insulating board was used as a source of cellulosic fire, while rigid PVC boards were used to line the walls of the chamber. In some experiments sticks of PVC were incorporated directly into the wood crib. The crib was ignited electrically. In all tests burning started with the crib smouldering and producing dense smoke for a few minutes, which was followed by a flash ignition of the smoke. After that the mode of burning varied with the size of the vent. With 5 cm vent (equivalent in an average room to an open fanlight) flash ignition was followed by smouldering combustion. With 10 cm vent (equivalent to an open door) smouldering alternated with the flash ignition, and with 15 cm vent the flash ignition was generally followed by continuous flaming combustion. In all the tests hydrogen chloride was evolved later than carbon monoxide, the delay increasing with decreasing vent size. In tests with 5 cm vent the delay was minimum 30 min but usually much longer when PVC was used as wall lining. Shorter delays occurred when PVC was incorporated directly into the crib but the rates of evolution were lower. In all tests carbon monoxide was evolved a few minutes after ignition. The rate of evolution was little affected by wall linings of PVC but was reduced when PVC was incorporated in the crib.

In assessing the effect of PVC in burning compartments on the toxic gases escaping into the remainder of the building, for the worst condition that no gases escape outside the building, following conclusions were drawn:

1) The results indicate that when the ventilation is small, hydrogen chloride from PVC would make little or no contribution to the hazard already presented by carbon monoxide from traditional cellulosic combustibles. Assuming that the rate of combustion is determined solely by ventilation the author calculated from his experimental results that about 30 cubic meters of carbon monoxide would be generated in the first hour from the room 4 m$\times$4 m$\times$3 m high, ventilated through an opening 1 m$\times$0.5 m at the top of the room. This amount of carbon monoxide could contaminate 10,000 cubic meters to a level hazardous to life, this volume being many times the volume of the average dwelling space. Considering that the lethal concentration of hydrogen chloride for half-hour exposure (1,500 ppm) is 15 times higher than the concentration at which it becomes intolerable to breathe, the presence of hydrogen chloride may actually serve as a warning in cases of smouldering fires that may go undetected for a longer period of time.

2) In cases when the ventilation is substantially higher and the flaming fire develops quickly, a substantial part of the plastic would be burnt in the first hour. In those cases the maximum amount of risk due to hydrogen chloride can be calculated from the amount of PVC present. It can be shown that, in terms of toxicity, the hydrogen chloride from 0.1 mm plastic coating on wallpaper in a room does not add appreciably to the risk presented by normal content of cellulosic matter. For greater loads of PVC full account must be taken of the actual rate of evolution of hydrogen chloride which has been shown to vary with time. The irritating effect of lower concentrations of hydrogen chloride could, however, augment the effects of smoke and other gases in hampering escape and rescue efforts.

The above assessments were made on the assumption that the size of the burning compartment has no effect on the rate of combustion of the plastic. Large-scale tests in a compartment 4 m$\times$4 m$\times$3 m high are being conducted presently; fuller account of all the tests will be published later.

Wenzel, H. G. "Relationship between Human Body Temperature and Pulse Rate when Performing Physical Work in a Warm Climate," *Int. Z. Agnew. Physiol.* 26 (1), 43–94 (June 1968)

Section: K
Subjects: Body temperature; Climates, warm; Human body temperature; Humidity; Physiological: Pulse rate; Warm climates; Work

Abstract by Safety in Mines Research Establishment, England. from *Occup. Sfty Hlth Abstr.* 7 (7), 1969. Reprinted by permission,

Research done with financial support from the ECSC. An introductory discussion of the literature is followed by a description of the experimental methods. One hundred five work tests were carried out in a controlled temperature and humidity chamber, where the test subject performed differing types of heavy work on a treadmill under various simulated climatic conditions. Body temperature was measured rectally and in the external auditory canal to determine the relationships between these two temperatures and between pulse rate and ear temperature. The data are fully reproduced and described. The varying relationships between metabolism and body temperatures in warm and normal environments suggested that when physical effort exceeds the endurance limit for normal climatic conditions, body temperatures cease to be constant and heat accumulation contributes to the limitation of physical endurance.

Žáček, I. "Determination of Energy Expenditure under Work and Heat Load," *Pracovní Lék.* 21 (6), 240–246 (August 1969). In Czech.

Section: K
Subjects: Energy expenditure; Heat load; Work load

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An analysis of measurements made on 312 men showed that the net energy expenditure during a shift can be estimated with sufficient accuracy by means of a formula based on the sweat rate and a time-dependent mean of the tempeatures at which work is performed at various distances from the source of heat, taking into account the amount of clothing worn and the intake of liquids during a shift. A maximum perspiration of 2500 g during a shift is proposed as an index of the permissible energy expenditure under various combinations of clothing and temperatures. A scheme for shortening the working hours according to the amount by which the sweat rate exceeds the amount permissible in given conditions is put forward. A relation is established between the effect of a reduction of the temperature as defined above on the sweat rate and the reduction in energy expenditure with various amounts of clothing worn. This shows that a suitable reduction of the ambient temperature will have the same effect on working efficiency as a reduction in energy expenditure.

L. Operations Research, Mathematical Methods, and Statistics

Chandler, S. E. (Joint Fire Research Organization, Borehamwood, England) "Multiple Death Fires," *Joint Fire Research Organization Fire Research Technical Paper No. 22* (1969)

Section: L
Subjects: Deaths, multiple; Fire deaths; Multiple deaths; Statistics, fire deaths

Author's Abstract

The annual incidence of multiple-death fires has been increasing over the last few years. In the period 1960–1966, fire brigades reported 373 such incidents and 368 of their reports were used in this survey. There were 302 fires in buildings (237 occurred in dwellings); outdoor incidents numbered 66. If the 237 incidents in dwellings, 142 (about 60 percent) occurred in buildings erected before 1910 (approximately 30 percent of all buildings).

About two-thirds of the incidents occurred between October and March; the period of severe weather in the first three months of 1963 alone gave rise to 31 multiple-death fires.

Nearly 36 percent of the fires were of unknown cause; smoking materials accounted for nearly 13 percent and oil heaters about 10 percent. In nearly 23 percent of the fires furniture or furnishings were ignited; the proportion of these increased during the seven-year period.

Of the 1,000 people who died in the incidents, 59 percent were asphyxiated and 31 percent received fatal burns. These incidents also gave rise to about 500 non-fatal casualties.

Nearly 60 percent of the victims were males.

Three hundred fifty-nine children ages five and under died, and 82 fatalities were recorded in the over sixty-five age group.

It is likely that in at least one-third of the incidents in dwellings, a major factor in assisting the spread of fire and toxic gases was the failure to keep doors shut.

Multiple-death fires occur most frequently in areas in which multiple occupancy in dwellings is common and this, together with the fact that furniture and furnishings are often the materials ignited first, indicates overcrowding as an important factor.

TABLE 1

Deaths by Fire 1960–1967

Source	1960	1961	1962	1963	1964	1965	1966	1967
Fire Research Station (UK)	529	572	667	818	681	703	780	773
Registrars General (UK) (Classification E.916)	800	804	962	1076	918	925	948*	**

* Excluding Northern Ireland.
** Not yet available.

Chandler, S. E. (Joint Fire Research Organization, Borehamwood, England) "Fires in Hotels," *Joint Fire Research Organization Fire Research Technical* Paper No. 23 (September 1969)*

Section: L
Subject: Hotel fires

Author's Summary

Recent loss of life in hotel fires and similar occupancies in which there are large numbers of people at risk has prompted this study of reports of hotel fires attended by fire brigades, of which the annual frequency was about 700 until 1967. The reports used for the study were those of fires attended during 1966 (the latest year for which complete statistics were available at the time of writing).

The proportion of fires that occur during sleeping hours in hotels is nearly twice that in private dwellings. "Smoking materials" is the most frequently reported cause, accounting for over 20 percent, compared with about 9 percent in private dwellings. Fires attributed to cooking and space-heating appliances, electric wire and cable, are also quite common.

About 20 percent start in kitchens—these are mainly during the daytime; fires starting in bedrooms and bedsitters amount to 17 percent of the total. About 11 percent start in halls and bars; nearly half of these are discovered during sleeping hours and smoking materials account for a high proportion of them.

About 53 percent are tackled, and nearly half of these are extinguished, before the arrival of the brigade. About three-quarters of the fires which require brigade attention are confined to the room of origin.

At least half occur in premises built before 1900. Most of the hotels have timber floors and timber is also prominent in the construction of the roofs. There is evidence to suggest that fires in older buildings are more likely to spread than those in more recent ones.

One incident, in which there was extremely rapid spread, led to five deaths. During the year there were 9 fatal and 41 non-fatal casualties. In those incidents involving casualties which spread beyond the room of origin, the spread nearly always resulted from a door being left open or from an enclosed staircase.

Chandler, S. E. (Joint Fire Research Organization, Borehamwood, England) "Fire Deaths in the Third Quarter of 1969," *Joint Fire Research Organization Fire Research Note No. 794* (November 1969)

Section: L
Subjects: Fatalities; Fire statistics

Author's Abstract

A preliminary survey shows that 92 persons died in fires in the third quarter of 1969. Sixty-nine were in England and Wales, 20 in Scotland and three in Northern Ireland. This figure is lower than in either of the first and second quarters of the year.

Five firemen were killed as a result of an explosion in London.

* Post order to P.O. Box 569, London S.E.1, England. In the U.S. to British Information Agency, New York, N.Y.

M. Model Studies and Scaling Laws

Lee, B. T. (Naval Radiological Defense Laboratory, San Francisco, California) "Mass Fire Scaling with Electrically Heated Models," *NRDL Report TR69, Office of Civil Defense Task Order DAH20-67-C-0149, Work Unit 2536F* (May 1969)

Section: M
Subjects: Electrical fire model; Fire models; Model fires; Scaling

Author's Abstract

Electrical models based on partial scaling principles neglecting molecular transport parameters (as characterized, for example, by a Grasof number Gr), have been built at NRDL to scale the gross flow features of a mass fire down to laboratory size. The scaling rules require that the model be geometrically similar to the prototype, and that heat release rate per unit area be scaled as the square root of the characteristic horizontal dimension L. To the extent that these principles are valid, gas temperatures will be the same, and velocity scales as the square root of L, at homologous points of model and prototype flow fields.

Data in this report were obtained with two models which, when placed in a corner, simulated quadrants of a 2 foot by 2 foot and of a 4 foot by 4 foot fire. Both models consist of square arrays of electrical heating elements. Inflow air velocities at the edge of the models and updraft velocities in the hot air column above the models are measured with a hot wire anemometer. Air temperatures in the column are measured with chromel-alumel thermocouples.

The heat release rates used in the models corresponded to the scaled down estimated rates at 5 and 18 minutes after ignition in the June 1966 Project Flambeau fire. Measurements of air velocity and temperature over the quadrant of the 4 foot model appeared to scale favorably with data from the quadrant of the 2 foot model.

Scaled down inflow velocity around the June 1966 Flambeau fire and velocities and temperatures recorded at the near-street-level environment across the September 1967 Flambeau fire compared favorably with data at homologous points above the models.

Rockett, J. A. (National Bureau of Standards, Washington, D. C.) "Objectives and Pitfalls in the Simulation of Building Fires with a Computer," *Fire Technology* **5**, 311–322 (1969) **Barrett, R. E. and Locklin, D. W.** (Battelle Memorial Institute, Columbus, Ohio) "A Computer Technique for Predicting Smoke Movement in Tall Buildings," *Fire Technology* **5**, 299–310 (1969)

Section: M
Subjects: Building fires; Computer simulation; Smoke movement

Reviewed by H. A. Becker

The paper by Rockett contains a general discussion of problems encountered in the attempt to mathematically simulate building fires. Some of the features of a FIRE HISTORY computer program, on which work is in progress, are described. The paper by Barrett and Locklin, on the other hand, is concerned with a single aspect of the fire problem: the movement of smoke in tall buildings. The decoupling of smoke movement from the other fire phenomena is facilitated by the simplifying assumption that the gas flow in a large building, caused by the stack effect, is not significantly affected by a localized fire of small to medium intensity, and the smoke from the fire simply follows the existing air currents.

In Rockett's general treatment a building is divided into rectangular cubicles, each of which must be described as to geometry and fuel loading. The almost unavoidable assumption is made that each cubicle influences directly only its nearest neighbors, normally six. A general prescription for describing the fire in a cubicle is not offered, but an interesting idea is suggested: the fire behaviour of the fuel in a cubicle may be related to that of an equivalent crib. The extensive experimental knowledge of crib fires can then be drawn upon to fill the gap in the knowledge of fire behaviour in buildings.

Air movement is said to be a major source of problems in Rockett's scheme. There are few experimental data available, and the quality of a computed solution is often impossible to assess. Another difficulty is that, whereas in a small building all possibilities for open doors and windows might be examined, in a large building only a limited number can be checked. The selection of the most important cases involves great uncertainty.

In principle, though, the calculation of air movement poses no special difficulty. Except, presumably, for the dominance of orifices and slits, it should be similar to a piping network problem. Barrett and Locklin have computed air flows and pressures due to the stack effect in a hypothetical 75-story office building. Two cases are considered: (1) the "balance condition" of 75°F ambient air temperature and no wind, and (2) the "basic winter case" of 0°F and moderate wind. Both cases are considered under rush-hour conditions when occupants are entering and leaving the building at a high rate. The winter condition produces a pressure differential of 1.9 in. water across exterior walls at the top of the building. Forces developed by pressure differentials across some doors would make these difficult to open. Calculated air-flows indicate the expected direction and magnitude of smoke flows from fires small enough not to disturb the normal stack effect.

Mathematical models such as those discussed in these papers could be of great value in designing buildings for low fire hazard. The models are, however, still in a primitive state. The most immediate need appears to be for more and better data on the performance of real systems. Both papers note the paucity of information on flow resistances along air flow paths in buildings. The description of burning rate and fire spread is crude and tentative. In summary, it appears that a mathematical framework for modeling fires and fire effects in buildings has been developed in broad outline, but quantitative knowledge of the basic physics must be improved before much further progress can be made.

N. Instrumentation and Fire Equipment

Baker, A. R. "A Review of Methanometry" *Min. Engr.* **128** (107), 643–652 (August 1969)

Section: N
Subjects: Methanometry; Review

Abstract by Safety in Mines Research Establishment, England.
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Instruments for the detection and estimation of firedamp are becoming used more widely in the coal and other mines of many countries. This paper discusses the factors which influence the design of the instruments and reviews the various types of methanometer (including recorders and alarms) which have been used recently, or are intended for use in mines. Some of the factors affecting the choice of instrumentation and the method of application are discussed.

Daines, M. E. "The Preparation of Standard Gas Mixtures by a Gravimetric Technique," *Chemy Ind.* (31), 1047–1053 (August 1969)

Section: N
Subjects: Gas mixtures; Gravemetric standards; Standards

Abstract by Safety in Mines Research Establishment, England.
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The advantage claimed for this novel technique are: greater simplicity and accuracy than those of methods commonly used, elimination of accurate pressure and temperature measurements and of the use of compressibility factors. Using either a 200 g or 1 kg constant load balance, accurate mixtures of two or more gases in concentration ranges down to parts per million are prepared in aluminum alloy cylinders. Up to 65 litres of the mixture can be produced, sufficient for routine calibration of gas analysers. A cheap, simple apparatus for cylinder filling is also described.

Fuller, L. E., Parks, D. J., and Fletcher, E. A. (University of Minnesota, Minneapolis, Minnesota) "Flat Flames in Tubes—Easy Fundamental Flame Speed Measurements," *Combustion and Flame* 13 (5), 455–460 (1969)

Sections: N, G
Subjects: Burning velocity; Flame speed; Flat flames; Tube flames.

Reviewed by J. M. Singer

A tube method for determining flame speeds of gases is described. Downward or upward flame speed is measured in a 3.85 cm diameter, 68 cm long Pyrex tube equipped at each end with various combinations of screens, orifices, and electric spark ignition sites. One end of the tube is open to an appropriate orifice diameter, and the outer end closed so that following ignition, a flat flame propagates through the tube, interrupted through its travel by momentary periods of instability and recovery. The burning velocity is taken to be the constant speed of the undistorted flat flame in one of its intervals of travel. Apparently the appearance of a flat flame without curvature is due to the suppression of Poiseiulle flow in the burned gases behind the flame by formation of flow turbulence.

The tube method offers several advantages over the burner or nozzle method such as a relatively simple experimental setup and the use of small quantities that facilitate study of toxic, corrosive, and expensive reactants. The present measured values appear to be in general agreement with those of other investigators as shown by a comparison of burning velocity curves for propane-air. However, some disadvantages should be noted. The artifact of a confined propagating flat flame does not insure total success for correct burning velocity determinations. For example, a closer comparison of the present fundamental flame speeds of propane-air near the lower and upper flammability limits with accepted values of Harris, Grumer, von Elbe, and Lewis[1] indicates that quenching may have occurred for the confined flames; the tube method values are lower than the burner method values. The description of the experiments and equipment in this paper does not indicate any operating difficulties in manipulating the screens, orifices, and ignition characteristics for producing flat flame configurations. Yet a variety of investigators of flames in tubes have reported the occurrence of flame vibrations, flame curvature, and non-steady flame speeds, all influenced by aerodynamic interaction and heat loss to the walls. Additional discussion of these limitations would be welcome in a future paper.

Reference

1. Harris, M. E., Grumer, J., von Elbe, G., and Lewis, B.: "Burning Velocities, Quenching and Stability Data on Nonturbulent Flames of Methane and Propane with Oxygen and Nitrogen," *Third Symposium on Combustion and Flame and Explosion Phenomena,* The Williams and Wilkins Co., Baltimore, Maryland, 1949, p. 80–89.

Hockings, W. A. "Particle- and Grain-Size Measurement by X-ray Fluorescence," *Powder Technology* 3 (1), 29–40 (October 1969)

Section: N
Subjects: Grain; Particles; Size measurement; X-ray fluorescence

Abstract by Safety in Mines Research Establishment, England, from author's summary. Reprinted by permission.

A method of particle size measurement is presented which is based on the fact that the intensity of fluorescent X-rays from an element in a particle is dependent on particle size. The method is rapid and non-destructive, requires only a small amount of sample and permits measurement of the sizes of different particle species in a single sample.

Rasbash, D. J. (Joint Fire Research Organization, Borehamwood, England) "Notes on the Use of Smoke Extractors for Fire Fighting," *Joint Fire Research Organization Fire Research Note No. 772* (June 1969)

Section: N
Subjects: Extinguishing; Smoke extractor

FRAR Editor's Comment

This note provides guidance on the ways smoke extractors may be used to assist firemen. Attention is given to the problem of establishing and maintaining a layer of fresh air below a layer of hot smoke and the controlled use of a current of air to dilute smoke and to direct its flow.

Simms, D. L. (Joint Fire Research Organization, Borehamwood, England) "The Design of Test Methods for Industrial Fabrics for Protection against Fire," Based on paper given at Industrial Textiles Group Conference, May 6, 1965. *Textile Institute and Industry*, February 1966, pp. 43 and 44.

Section: N
Subjects: Fabrics; Fire protection; Textiles

Reviewed by H. M. Cassel

Three factors determine the fire hazard of a fabric: (1) ease of ignition; (2) rate of flame spread; (3) amount of heat liberated. Laboratory experiments have shown that for cellulose materials, and probably for most others, these factors are linked. By measuring either of the first two, estimates of the other can be obtained. For fabrics that spread flame, the rate of spreading can be used to estimate their hazard. This category is of importance for domestic rather than industrial fabrics. For domestic apparel that does not spread flame, where only the minimum thermal damage is permitted, the combination of a short duration of after-flaming with a small charred or melted area, ensures that any flame produced by the fabric and the heat transferred from it is small. The extent and duration of afterglow is important in the presence of flammable vapor.

The most hazardous position for any fabric is hanging freely while being ignited at the base by a flame impinging on both sides. Then, the upward traveling heat preheats the unburnt fabric. However in certain cases the vertical position is not the most dangerous. With fabrics capable of melting there is always the possibility that melting drops fall off without flame spreading. Also, twisted or folded fabric can burn where a flat piece does not. Present standard methods provide only for examination of flat pieces.

The minimum rate of heat transfer required for ignition is about 2 cal cm^{-2} sec^{-1}, which has to persist for several seconds. A gas burner of 3/8 in. diameter with a luminous flame 1.5 in. high is appropriate.

British Standards are included in the "Tests for Flameproof Fabrics" BS 3119/1959, and in the performance requirements for flameproof clothing, BS 3120/1959. Accordingly, a narrow strip of fabric is suspended vertically, a luminous flame from a bunsen burner is played on the lower edge till ignition starts and then is removed. The time any flame continues, and the extent of afterglow are noted. The length of fabric charred or melted is also measured. The duration of flaming on any specimen shall not exceed 8 sec, the afterglow shall not extend into the undamaged region, the maximum length charred or damaged shall not exceed 4 in.

Difficulties arose from the test methods themselves, and the performance requirements, particularly due to differences in behavior of the test strip and the whole piece of fabric. Much more stringent and carefully worked-out performance requirements are therefore now being attempted by the Committee of Directors of Textile Research Associations. Manufacturers who wish to be certain that their fabrics pass the test should aim at a higher standard than the pass mark.

Wraight, H. (Joint Fire Research Organization, Borehamwood, England) "The Development of a Foil Heat Flux Meter," *Joint Fire Research Organization Fire Research Note No. 790* (November 1969)

Section: N
Subjects: Convection; Heat transfer; Infrared; Measurement; Radiation; Radiometer; Window

Author's Abstract

An instrument has been developed for measuring heat flux in the range from 0 to 10 W/cm^2. It is of robust construction, suitable for outdoor use and designed so that it can be mounted flush with a surface to which the heat transfer is required to be measured.

The output of the instrument is proportional to the heat flux falling on it in the range from 0 to 5 W/cm^2 and at 8 W/cm^2 the deviation from direct proportionality is not more than 6 percent. The sensitivity is sufficient to enable a change in heat flux of 0.1 W/cm^2 to be detected.

By using the heat flux meter with and without an infrared transmission window on the front, values of both the radiated and convected heat transfer can be obtained. The instrument is not very sensitive to draughts even without the transmission window, but with it the output is rendered completely unaffected by draught for all practical purposes.

O. Miscellaneous

"Spacecraft Fires," Volume 1 of 2 Volumes (DDC-TAS-69-15). A bibliography. (Alexandria Virginia: Defense Documentation Center, July 1969), 89 pp. plus indexes. Availability: As AD-689 800 from Clearing house for Federal Scientific and Technical Information, Springfield, Virginia 22151. $3.00

Section: O
Snbjects: Fires, spacecraft; Spacecraft fires

Editorial material from *Fire Technology.* Reprinted by permission.

This volume is a compilation of 89 classified and unlimited references of documents relating to fire hazards and fire protection in spacecraft. The documents span a period from January 1953 to December 1968. Each report is identified by title and an AD number by which it may be obtained from the Clearinghouse for Federal Scientific and Technical Information. Further identification includes contract number, contractor, and author. Descriptors, or key words, and an abstract are given for each entry.

Greenfeld, S. H., Warner, Elizabeth R., and Reinhart, Hilda W. (National Bureau of Standards, Washington, D. C.) "Bibliographies on Fabric Flammability: 1. Wearing Apparel; 2. Fabrics Used on Beds; 3. Carpets and Rugs," *National Bureau of Standards Technical Note No. 498* (February 1970)

Section: O
Subjects: Apparel; Bedding; Beds; Blankets; Carpets; Clothing; Fabrics; Fibers; Fire; Flame; Flammability; Flammable; Floor coverings; Mattresses; Pillow cases; Pillows; Rugs; Sheets; Springs; Wearing apparel

Authors' Abstract

As recognition of the urgency of the flammable fabrics problem, the Flammable Fabrics Act of 1953 was amended in 1967 to include all items of wearing apparel and interior furnishings. In order to facilitate research and assist in the development of new standards and test methods in these areas, a series of bibliographies is being prepared by the NBS Office of Flammable Fabrics. The first three, on wearing apparel, bed fabrics, and carpets and rugs, are included in this Technical Note.

Malhotra, H. L. (Joint Fire Research Organization, Borehamwood, England) and **Crowder, J.** (Building Research Station, England) "Weathering Properties of Fire-Retardant Plastics Rooflights," *Joint Fire Research Organization Fire Research Note No. 11*

Section: O
Subjects: Fire retardants; Plastics; Rooflights; Weathering

Authors' Summary

An investigation has been carried out to determine the durability of fire-retardant treatments applied to glass-fibre reinforced polyester resin roof sheets when they are exposed to outside weathering conditions. Five different types of products were used and tested at intervals after a maximum exposure of four years.

Some early deterioration was noticed in the fire tests applicable to roof constructions but after one year the materials regained their original standard of performance and after four years there was an improvement in all cases.

All materials showed a degradation in their light transmission properties and in some cases there was a marked reduction. Materials which gave the best fire performance also had poorer weathering qualities.

Robertson, A. F. (National Bureau of Standards, Washington, D. C.) "U.S. Department of Commerce and the Flammability of Clothing Fabric," *Bulletin of the New York Academy of Medicine, Second Series* 43, 706–710 (August 1967)

Section: O
Subjects: Bureau of Standards, U.S.A.; Clothing fires; Department of Commerce; Fabrics; Flammability

Reviewed by H. M. Cassel

A monetary waste of roughly 1% of the gross national product is no suitable assessment of the personal tragedies of about 12,000 fire fatalities and 250,000 serious injuries from burns that occur each year. By the "Flammable Fabrics Act" of 1953 the Commercial Standards CS-191-53 and CS-192-53 were promulgated as the official means for determining the flammability of materials used for clothing.

The responsibility was delegated to the National Bureau of Standards, Fire Research Section, under its chief, A. F. Robertson.

Several groups have encouraged the adoption of NFPA Standard 702 which uses the same test equipment as CS-191-53, but differs primarily by application of the flame continuously to the edge of the specimen rather than for one second to the surface. The National Bureau of Standards has explored this procedure and the effect it might have on the type of fabrics considered acceptable. The surprising result was that perhaps as few as 2% of the fabrics might be classified differently. However, the burden of testing would be seriously increased since the NFPA test requires all fabrics to be ignited. Nevertheless, it is evident that NFPA Standard 702 does not provide a useful basis for the selection of significantly less hazardous fabrics. Indeed, we must await results of the survey of accidents from burns that is now in progress with the cooperation of the U.S. Public Health Service, to determine whether any but a drastic change in the method of testing would be useful as a basis for achieving significant reductions in accidental burns.

The results obtained, so far, are in satisfactory agreement with British and Canadian tests based upon the BS 3119 and 3120 specifications.

Remarkable is the amazing fact that about 60% of clothing-fire accidents originate in one way or another from careless use of flammable liquids, mostly gasoline, for burning trash. To date it clearly appears that no significant reduction in the number of accidents from burning cloth in can be achieved without major improvements in the flammable behavior of clothing fabrics. It is hoped industry will continue the development of permanently retardant-treated fabrics economically, esthetically, and usefully acceptable to the public. Thus clothing-fire injuries may be significantly reduced, although, of course, not eliminated.

BOOKS

Fire Test Performance, A Symposium (Winter Meeting of American Society for Testing and Materials, Denver, Colorado, February 1969) *ASTM Special Technical Publication No. 464.* $19.50 243 pp.

Eleven papers present critical surveys of a number of current fire performance tests. They cover a variety of subjects, but have a common theme, which is the need for improved and more meaningful tests. It is a healthy sign that such critical analyses are being made. Present problems are manifold and include not only the shortcomings in the tests, but also problems associated with the continuous influx of new materials and configurations which often make present testing methods obsolete. A critical need exists for more meaningful tests and improvement in passing information on new and modified materials to users in the field.

Authors' abstracts of the papers are presented herewith. This volume provides an excellent survey of current practices and opinions on fire testing.

Robert M. Fristrom, *Editor*

Robertson, A. F. and Gross, D. (National Bureau of Standards, Washington, D. C.) "Fire Load, Fire Severity and Fire Endurance"

Sections: A, G
Subjects: Burnout; Evaluation; Experimental fires; Fire endurance; Fire severity; Fire ventilation; Fires in buildings; Tests

A review is presented of fire studies beginning with the work of Ingberg at the National Bureau of Standards, who attempted to relate the severity of a fire endurance test in the laboratory to the conditions existing during actual building fires. He showed the importance of weight of combustibles per unit floor area as a major factor. He recognized the importance of ventilation in controlling fire behavior but did not specify it as a separate variable. Fujita in Japan is credited with emphasizing the importance of ventilation. His work has been followed and enlarged by others around the world. Ventilation parameters, compartment geometry, and fuel arrangement have been shown to exert a powerful influence. The radiance from a burning building is dependent to a large extent on the nature of the ventilating openings. Fire severity is not well defined, since it depends on the interaction of the temperature-time curve developed during a fire and the thermophysical properties of the materials exposed. There is a great need for further research on the influence of fuel arrangement, building geometry, and ventilation on fires in buildings.

Kai Odeen (National Institute for Testing Materials, Stockholm, Sweden) "Standard Fire Endurance Tests—Discussion, Criticism, and Alternatives"

Sections: A, G
Subjects: Combustion; Endurance tests; Evaluation tests; Fire temperature; Fire test; Heat transfer; Structural members; Thermal properties

This paper will give a survey of my own investigations in this field, as well as those which have been performed by other authors. The main outlines of an advanced method of fire technical design is described in accordance with the new Swedish regulations. These have been used for only a few months; therefore, the experiences are quite naturally not very extensive. However, it seems as if this method will make it possible to decrease the costs for fire protection without reducing the degree of safety. The method has turned out to be very useful especially when studying steel structures.

Standardized fire tests are based on the assumption that the temperature-time development of the fire is following the so-called "standard fire curve." This assumption is extremely simplified and in most cases hardly realistic. On the basis of a simple heat balance equation for the fire cell it is possible to compute the temperature-time development of the fire taking into account all relevant factors such as rate of combustion, amount of fuel (fire load), heat transfer conditions at the heated surfaces, and thermal properties of the structures enclosing and enclosed in the fire. A lot of numerical results will be included in the paper, that is, temperature-time curves for use as alternatives to the standard method which have been included in the new Swedish regulations. On the basis of the computed results there also will be given a proposal for another test procedure which probably will give results closer to those at a real fire.

This paper also will give results from fire tests under very "pure" conditions with wood fuel as well as with kerosine. It has been possible to make comparisons between recorded and computed temperatures, and good correlation is established. The influence of wood fuel on the fire characteristics of varying air supply, amount of fuel, and varying degrees of atomization of the fuel particles has been studied.

Examples will be given of the effect on structural members of different types of temperature-time developments, and some examples of use in structural design of the technique will be described also.

Seigel, L. G. (Applied Research Laboratory, U.S. Steel Corporation, Monroeville Pennsylvania) "Effect of Furnace Design on Fire Endurance Test Results"

Sections: A, G
Subjects: Design; Evaluation tests; Fire endurance; Fire resistance; Fire tests, Furnace tests; Furnaces; Tests

This paper is concerned with the influence of furnace design and operation on fire resistance ratings. Consideration is given to such factors as radiation and convection heat transfer, furnace pressure and gas flow, and dimensional effects.

As a result of this investigation, it is concluded that the total intensity of fire exposure maintained in the ASTM Methods E 119 furnace may not be affected seriously by furnace design so long as the thermocouples that control and indicate furnace temperature have approximately the same exposure to the fire as the specimen being tested. However, differences in furnace pressure and specimen size may cause serious differences in fire endurance test results.

Gustaferro, A. H. (Portland Cement Association Research and Development Laboratories, Skokie, Illinois) "Temperature Criteria at Failure"

Section: A
Subjects: Beams; Concrete; Evaluation; Failure; Fire tests; Floors; Reinforced concrete; Restraint; Roofs, Slabs, Steel construction; Tests; Thermal expansion; Walls.

ASTM Methods E 119 designate several temperature criteria as end points for fire tests. In tests of walls, floors, and roofs, the temperature rise of the unexposed surface is limited to 250°F average or 325°F at any one point. Steel temperatures are limited in tests of certain types of elements. This paper examines the background for these temperature limits by reviewing published data; new data are presented in some cases. The unexposed surface temperature criteria should be re-examined. Limiting steel temperatures are not valid for structural members in which the stresses are altered significantly by the effects of fire.

Harmathy, T. Z. and Lie, T. T. (Division of Building Research, National Research Council, Ottawa, Canada) "Fire Test Standard in the Light of Fire Research"

Section: A
Subjects: Effect of moisture; Evaluation; Failure in fire; Fire endurance; Fire load; Fire prevention; Fire research; Fire severity; Fire tests; Restraint; Specimen size; Standards; Temperature measurement; Temperature of failure; Test furnace; Test report; Tests

Because of the inadequacy of the fire load concept and of the large subject area covered by ASTM Methods E 119, the results of standard fire tests do not represent either the times for which building elements actually withstand building fires, or "rating" values expressing the "fire endurance quality" of the various building elements on a unique scale. Several areas of the standard are discussed where fire research indicates the need for urgent revisions. To achieve higher economy in design for fire endurance it will become necessary to replace the temperature-time curve by realistic heat flux-time relations characteristic of the specific conditions. For some decades to come progress in fire endurance research will be measured by progress in understanding building material behavior at elevated temperatures.

Goldberg, A. (Bureau of Building Inspection, Department of Public Works, San Francisco, California) "A Building Official's View Concerning Fire Test Standards"

Section: A
Subjects: Damageability; Durability; Evaluation; Fire doors; Fire prevention; Fire tests; Fire windows; Floor penetrations; Inspection; Spray-applied fireproofing; Standards; Tests

The use of ASTM standards by building officials and others who are not familar with the details involved in the evolution of the standards, nor the tests presents problems. On the other hand, the preparation and development of standards without recognizing the requirements of modern construction is unrealistic. An outline of certain of these areas of inadequacy is presented and suggestions made to improve the communication problem between standard making organizations and the user regarding fire test standards.

I hope my remarks might emphasize those made by several other authors. Some of my comments may be a rehash of things said by others; however, I believe it is essential that ASTM Committee E-5 on Fire Tests of Materials and Construction recognize its obligation not only to ASTM but also the public that relies upon the ASTM standards for safety.

Bono, J. A. (Underwriters' Laboratories, Chicago, Illinois) "New Criteria for Fire Endurance Tests"

Section: A
Subjects: Building construction; Evaluation; Fire endurance; Fire resistance; Fire restraint; Fire tests; Temperature criteria; Tests

The long accepted test procedure for determining the fire endurance of floor and roof assemblies, as described in ASTM Standard Methods of Fire Tests of Building Construction and Materials (Designation: E 119), is being questioned seriously. Skepticism has developed because the performance under fire exposure of structural members and assemblies has not corresponded with anticipated performance based on established properties of materials at elevated temperatures. The difference between predicted results and actual results is attributed to the test procedures used to implement provision in the Standard which require restraint of the test specimen and imposition of loads to develop working stresses. Restraint of the test specimen has contributed so substantially to the performance that normal structural criteria such as deflection and collapse appear to be of limited value in judging fire endurance.

Research projects have established that significant improvement is brought about by the presense of restraint during fire tests. Individual steel beams have resisted collapse in fire tests for a 25 percent longer time when tested under restraint as compared with simply supported tests. Concrete members have shown in excess of 400 percent increase in fire resistance in comparative tests.

Certain constructions employing continuity and cantilevered sections have shown improved fire resistance as compared with simply supported structures.

Various revisions of the criteria in ASTM Methods E 119 have been proposed. Each of these, developed in 1964, 1965, 1967, 1968, and 1969, provided partial solutions. With the exception of the 1969 proposal, which is before ASTM Committee E-5 at this writing, some features of each proposal have been criticized. The concepts of these proposals are examined in this paper, with a summary of the prevailing views. The impact on future designs of building construction for fire resistance and on the costs of building construction are so great as to make any changes in criteria a most important and difficult decision.

Gross, D. and Natrella, M. G. (National Bureau of Standards, Washington, D. C.) "Interlaboratory Comparison of the Potential Heat Test Method"

Section: A
Subjects: Calorimetry; Combustibility; Evaluation; Fire tests, Heat of combustion; Interlaboratory tests; Oxygen bomb; Potential heat; Tests

Quantitative measurements of the total heat release by selected building materials were made during an interlaboratory study of the Potential Heat Method. Seven of the eleven participating laboratories ranked the five materials in the same order, and a single ranking change for three other laboratories would yield identical rankings. The general magnitude of within-laboratory repeatability and between-laboratory reproducibility for composite materials of generally low potential heat are indicated by statistical analysis of the results.

Results are reported on the effect of the amount of combustion promoter used and on differences in the first and second phase values. A discussion is presented on the effects of material sampling and on certain features of the experimental procedure which require special care. A tentative test method standard, containing complete details of the test procedure, is included as an appendix.

Issen, L. A. (National Bureau of Standards, Washington, D. C.), **Gustaferro, A. H. and Carlson, C. C.** (Portland Cement Association, Skokie, Illinois) "Fire Tests of Concrete Members: An Improved Method for Estimating Thermal Restraint Forces"

Section: A
Subjects: Buildings; Concretes; Evaluation; Fire tests; Floors; Prestressed concrete; Reinforced concrete; Restraints; Roofs; Tests; Thermal expansion

An earlier exploratory study on the effects of restraint of thermal expansion on the fire resistance of prestressed concrete showed that for similar specimens, made of normal weight concrete, maximum thermal thrust was a function of the allowed linear expansion. In the present study, data were obtained for three additional groups of specimens: lightweight prestressed, lightweight reinforced, and normal weight reinforced. A method is presented for estimating the maximum thermal thrust that occurs during a fire test of a concrete floor, roof, or beam. Results of 12 fire tests of restrained concrete flexural members indicate that the method predicts the maximum thrust within about 15 percent. The method is applicable to specimens restrained both longitudinally and laterally as well as those restrained in only one direction. The method underestimates thrust for specimens with embedded underfloor ducts and overestimates thrust for specimens partly insulated from direct contact with the fire. In all 43 fire tests the specimens supported their loads considerably longer than would have been anticipated for either simply supported or fully restrained conditions.

Harmathy, T. Z. and Stanzak, W. W. (Division of Building Research, National Research Council, Ottawa, Canada) "Elevated-Temperature Tensile and Creep Properties of Some Structural and Prestressing Steels"

Section: A
Subjects: Creep properties; Elevated-temperature tests; Elongation; Evaluation; Prestressing steels; Reduction of area; Secondary creep rate; Structural steels; Tensile properties; Tests; Ultimate strength; Yield strength

The tensile and creep characteristics of two structural steels (ASTM A36 and CSA G40.12) and a prestressing steel (ASTM A421, all three used extensively in the building industry, have been investigated. Information is presented concerning the initial portion of the stress-strain curve, the ultimate and yield strengths, the elongation, the reduction of area, and the two stress-dependent creep parameters, Z and ϵ_{t0}, for temperatures up to 1200° and 1300°F.

The tensile data obtained for ASTM A36 steel seemed to agree with other reported data. The G40.12 steel exhibited somewhat unusual tensile behavior at about 700°F. For the ASTM A421 steel the natural scatter of the test data overshadowed the effect of crosshead speed (0.02 to 0.75 in./min) at temperatures below 700°F. Harmathy's creep model seemed fairly well applicable to all three steels, and Clauss' rule concerning the creep rupture time to the two structural steels.

Harmathy, T. Z. (Division of Building Research, National Research Council, Ottawa, Canada) "Thermal Performance of Concrete Masonry Walls in Fire"

Section: A
Subjects: Computer prediction; Concrete; Design criteria; Evaluation; Fire endurance; Lightweight concrete; Masonry units; Masonry walls; Tests; Thermal performance; Thermal properties; Walls

Eleven hundred eighty computer calculations have been performed to study the heat flow in fire through concrete masonry unit walls. They covered wide ranges of the four geometric variables, and four concretes which could be regarded as "limiting materials" in the normal weight and lightweight groups. It was possible to express the thermal fire endurances of the masonry units in dry condition with the aid of three empirical equations. These equations can be used to estimate the fire endurance from the geometric variables and material properties only in the case of concretes made with chemically stable aggregates. Their real usefulness lies in showing the way to economical design and, as extrapolation formulas, in extending test information to geometries and materials not covered by fire tests.

Directory of Fire Research in the United States, 1967–1969 (Fifth Edition)—Committee on Fire Research, NAS-NRC. E. J. Whipple, ed. 376 pages. National Academy of Sciences, Washington, D. C. 1970*

This biennial Directory provides one of the few indices of the intensity and character of fire research in this country. Taken at face value, interest has increased in fire research during the two years since the previous directory (1965–1967). The number of reporting laboratories has increased from 84 to 111, and the number of projects reported from 318 to 432. As a consequence, the size of the Directory has increased, partly because of improved coverage and the reporting of many projects peripheral to fire research. However, the reviewer hopes that this indicates an increase in interest. Since the Directory covers the past two years, it does not reflect the present difficult conditions in science.

Projects are listed alphabetically, according to laboratory, under three categories: federal government laboratories; universities; and industrial and private laboratories. Research summaries are provided and the names of laboratory directors, project supervisors, and sponsors are given. Projects are cross-indexed by sponsor, subject, and laboratory. The Directory provides an excellent reference to fire research in the United States. It is a service to the fire community, and the editor, Mrs. E. J. Whipple, is to be congratulated for compiling this useful volume.

JOURNALS

Fire Control Notes. Published quarterly by the Department of Commerce, U.S. Forest Service.**

Section: O
Subjects: Air operations; Damage; Detection; Equipment and supplies; Fuel treatment; Fuels; Hazard; Ignition; Mop-up; Prepardness; Prescribed burning; Prevention; Suppression; Training; Weather

This publication contains short notes or articles (typically of 500 to 1,000 words) on items of interest in forest fire control. The articles are too short for efficient abstracting; therefore, we have decided to bring this information to the attention of the FRAR readers by publishing the yearly subject index. The articles are arranged according to subject and occasionally are listed more than once. The identification numbers following the titles give the issue numbers followed by page numbers. Each issue is paged separately. Beginning with Volume 31 (1970) we plan to publish the Table of Contents of each issue as it is received.

Robert M. Fristrom, *Editor*

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Fire Control Notes Subject Index (1969)

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Tolin, E. T., Davis, J. B., and Mandt, C. (U.S. Forest Service Forest Fire Laboratory, Riverside, California and Transportation System Planning Study, Division of Engineering, Region 5, U.S. Forest Service, San Francisco, California) "Automated Forest Fire Dispatching—A Progress Report," p. 4

Authors' Abstract

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MEETINGS

Central States Section of The Combustion Institute, April 7 and 8, 1970
Manned Spacecraft Center, National Aeronautics and Space Administration, Houston, Texas (Co-sponsored by IIT Research Institute)

Disaster Hazards—1970 Technical Session

TECHNICAL PROGRAM

Meeting Chairman: Dr. Richard J. Priem
Head, Rocket Combustion Section
Lewis Research Center
National Aeronautics and Space Administration

Program Chairman: Mrs. Hyla S. Napadensky
Senior Engineer, Engineering Mechanics Division
IIT Research Institute

SESSION I—*Systems Safety*

Chairman: Mr. R. G. Perkins, Safety Engineer
Armed Services Explosive Safety Board

Application of Systems Safety Analysis to Evaluate and Predict Disaster Hazards
J. Umlauf
Logic Simulation Co.

Blast Hazards to Nuclear Power Packages Mounted on Space Launch Vehicles
J. M. Bowyer, Jr.
Texas Eastern Transmission Corp.

Custom Designed Blast Resistant Structures
R. M. Rindner, and S. Wachtell
Picatinny Arsenal

Accidental Initiation Mechanisms for Large Solid Propellant Motors
H. S. Napadensky
IIT Research Institute

SESSION II-A—*Hazards of Marginal Explosives*

Chairman: Dr. J. F. Masi, Chief
Propulsion Division
Air Force Office of Scientific Research

Hazards in the Marine Transportation of Liquefied Natural Gas
J. N. Murphy, D. S. Burgess and R. W. Van Dolah
Bureau of Mines, Safety Research Center

Atmospheric Diffusion and Deflagration of Boil-Off Vapors Associated with a Spillage of Liquefied Natural Gas
R. J. Sergeant
Systems Group of TRW Inc.

The Influence of Heat Loss on Compression Ignition in Pneumatic Systems
G. M. Faeth
Pennsylvania State University

Safe Separation Distances from Liquid Fuel Storage Areas
S. Atallah and D. S. Allen, Arthur D. Little, Inc. and A. F. Sarofim, MIT

SESSION II-B—*Hazards of Marginal Explosives*

Chairman: Lt. Col. R. W. Haffner
Project Scientist, Propulsion Division
Air Force Office of Scientific Research

Shock Waves in Air Generated by Deflagration Explosions
S. R. Brinkley, Jr.
Combustion and Explosives Research, Inc.

Suppressing Aluminum Dust Explosions
L. A. Eggleston
Southwest Research Institute

Initiation and Propagation of Explosive Reactions in Chlorine-Ethane Mixtures
W. W. Lawrence and S. E. Cook
Ethyl Corporation

The Armed Services Explosives Safety Board
R. G. Perkins
ASESB

SESSION III—*Toxicity*

Chairman: Dr. B. Brown,
Senior Technical Specialist
Chemical Propulsion Division
Hercules, Inc.

Toxic Effluents of Large Solid Rocket Motors
Lt. W. Burns, WTR, Vandenberg AFB, and Lt. Col. D. C. Daube, AFPRO

Control of the Toxic Effluents from Beryllium Rocket Motors during Simulated Altitude Testing
Capt. C. LaBlonde and Mr. D. W. Male
AEDC, Arnold Air Force Station

The Detection of Toxic Contaminants in the Atmosphere Using Single Ended Remote Raman Spectrometric Techniques
S. M. Klainer, T. Hirschfeld, E. R. Schildkraut, and M. J. Block
Block Engineering, Inc.

Flammability Properties and Combustion Products of Activated Charcoal Used in Atmospheric Purification
J. E. Johnson and F. J. Woods
Naval Research Laboratory

New Concept in the Design of Structures for Development of Explosive, Chemical and Pyrotechnic Materials
N. Dobbs, Ammann & Whitney, Consulting Engineers, and R. M. Rindner, Picatinny Arsenal

SESSION IV—*Insurance and Liability*

Chairman: Mr. G. M. Woods, Manager
Engineering, Kemper Insurance, Chicago

Estimating Future Losses, Probable and Maximum
W. H. Doyle
Factory Insurance Association

Explosion & Fire Experience in the Hydrocarbon Processing Industry
H. S. Robinson
Oil Insurance Association

Risk Evaluation in Chemical Plants
A. Spiegelman
American Insurance Association

Legal Liability Resulting from Disaster
A. B. Kelly
Factory Mutual Legal Department

Western States Section of The Combustion Institute, October 27 and 28, 1969. La Jolla, California.

27 October 1969: Session 1—Cellulose Pyrolysis; *Dr. A. Broido, Chairman*

Registration

Welcome and introductory remarks by Dr. S. S. Penner, University of California, San Diego

Paper 69–24: Graphical Resolution of Thermogravimetric Analysis Curves for Ammonia-Swelled Cellulose, A. Broido and M. Weinstein, Pacific Southwest Forest and Range Experiment Station, U.S. Forest Service.

Paper 69–25: A Simplified Model for the Decomposition of Cellulose, Anne E. Lipska, U.S. Naval Radiological Defense Laboratory.

Paper 69–26: Some Considerations Pertaining to the Problem of Wood-Burning, A. Murty Kanury and Perry L. Blackshear, Jr., University of Minnesota.

Paper 69–27: Analytical Study of Pyrolysis, including the Effects of Mass Loss and Competing Reactions, Ronald L. Panton and Jerrold G. Rittman, Oklahoma State University.

Paper 69–28: The Burning of Carbonaceous Materials as a Destructive Distillation Process, Gilbert S. Bahn, The Marquardt Company.

Paper 69–29: Chemical Models for Combustion and Atmospheric Pollution, Andrew M. Stein, Forest Fire Laboratory (Riverside), U.S. Forest Service.

Session 2—Flame Spread; *Dr. R. C. Corlett, Chairman*

Paper 69–30: Temperature Gradient Structure near the Surface of Burning Liquids, H. B. Peterson and R. L. Gipe, Naval Research Laboratory.

Paper 69–31: Flame Spreading above Liquid Fuels; Surface-Tension Driven Flows, W. A. Sirignano and I. Glassman, Princeton University.

Paper 69–32: Influence of Laboratory Parameters on Flame Spread across a Liquid Fuel, R. Mackinven, J. G. Hansel, and I. Glassman, Princeton University.

Paper 69–33: Some Recent Experimental Observations on Flame Spreading over Solid Fuel Surfaces, R. F. McAlvey III, R. S. Magee, P. M. Baham, and F. A. Lastrina, Stevens Institute of Technology.

Paper 69–34: Development of Nonflammable Coating for Polycarbonate, M. C. Willson and C. E. Semler, Monsanto Research Corporation.

Paper 69–35: Apparatus for Determining the Glowing Combustibility of Thin Cellulosic Materials, D. C. Jones and A. Broido, Pacific Southwest Forest and Range Experiment Station, U.S. Forest Service.

28 October 1969: Session 1—Larger Fires; *Dr. P. L. Blackshear, Jr., Chairman*

Paper 69–36: Ignition and Extinction in Boundary Layers, A. Murty Kanury, Factory Mutual Research Corporation.

Paper 69–37: The Diffusion Flame Plume above Burning Alpha-cellulose Cylinders, Franklin J. Kosdon, University of California, San Diego.

Paper 69–38: Heat and Mass Transfer Phenomena in a Large Turbulent Flame, Byard D. Wood and Perry L. Blackshear, Jr., University of Minnesota.

Paper 69–39: Heat Transfer from a Burning Cotton Cloth to an Adjacent Isothermal Wall, Norman J. Alvares, University of Minnesota.

Paper 69–40: The Modeling of Pulsating Fires, George M. Byram and Ralph M. Nelson, Jr., Southeastern Forest Experiment Station, U.S. Forest Service.

Paper 69–41: Some Applications of the Laser in Fire Research, Floyd D. Maxwell, Forest Fire Laboratory (Riverside), U.S. Forest Service.

Session 2—Airbreathing Combustion and General Papers; *Dr. P. A. Libby, Chairman*

Paper 69–42: Combustion Technology Advancement Opportunity for Next Generation Jet Engines, E. V. Zettle, General Electric Company.

Paper 69–43: The Thermal Energy Equation for Turbulent Shear Flows, Roy J. Heyman, Martin Marietta Corporation.

Paper 69–44: A Theoretical Study of Combustion Stability in an Air-Liquid Fuel Combustion Zone, John M. Bonnell and Alexander Vranos, Pratt & Whitney Aircraft.

Paper 69–45: Concept of a Large Hot Air Breather Test Facility, G. A. Hosack, Rocketdyne.

Paper 69–46: Hydrodynamic Aspects of the Instability of Enclosed Laminar Diffusion Flames, P. Sampath and B. E. Deckker, University of Saskatchewan.

Paper 69–47: Ignition of Compound Porous Particles with Multistage Reactions, F. I. Honea and L. W. Ross, University of Denver.

Paper 69–48: Calculation of Shock Temperatures of Unreacted Liquid Carbon Tetrachloride and Nitromethane at Pressures up to 250 kbar, Michael Cowperthwaite and Robert Shaw, Stanford Research Institute.

Paper 69–49: The Hydrogen-Oxygen Difluoride Flame, A. D. Kirshenbaum, Temple University.

Preprints will be available *prepaid* while still available from the Preprints Chairman at the price of the registration fee. Make check ($10) payable to: Western States Section/The Combustion Institute. Send to: Professor Robert F. Sawyer, Preprints Chairman, WSS/CI, Mechanical Engineering-Thermal Systems, University of California, Berkeley, California 94720.

NASA Conference on Materials for Improved Fire Safety, May 6 and 7, 1970 Houston, Texas. Sponsored by the Manned Space Flight Safety Office*

Section: A
Subjects: Fire safety; Safety; Materials; Fire retardants

Technological fallout from development work by the National Aeronautics and Space Administration steadily increases. Massive amounts of it were presented by NASA speakers and exhibitors at the conference on materials for improved fire safety held at the Manned Spacecraft Center (MCS) near Houston, Tex., as they summarized work on fire-resistant materials performed largely since the January 1967 fire in an Apollo spacecraft.

Much of this work has been concerned with modifying and adapting materials to needs of the space program. Relatively few new compounds have been developed by NASA or its contractors. A multitude of composite materials that provide vary-

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ing degrees of fire resistance has been developed while maintaining or keeping at useful levels other properties such as flexibility, wearing comfort, abrasion resistance, and strength.

Several lightweight foams have been modified at the Ames Research Center of NASA for fuel-fire protection, said J. A. Parker, who delivered a paper prepared by Richard H. Fish, also of Ames. Urethane systems have polyvinyl chloride, potassium fluoroborate, or microencapsulated volatile halogen-bearing molecules added to them. PVC increases char yield, thus increasing thermal resistance. It also releases gaseous hydrochloric acid, which acts as a free-radical flame scavenger to reduce burning. Short glass or quartz fibers (about $\frac{1}{4}$ inch long) added to urethane systems give improved thermal properties.

Polyisocyanurate materials have been developed, but they suffer from brittleness, or friability, which limits their use in low-density applications. To reduce brittleness, urethane linkages are added to the polymer, usually by adding acrylonitrile because when heated nitrile linkages cyclize to form high-temperature stable heterocyclic rings, Mr. Parker found.

A copolymer of hexafluoropropylene and vinylidene fluoride, produced by 3M and sold under the tradename Fluorel, can be used in numerous forms to provide fire resistance, said Daniel E. Supkis of MSC. In forms fabricated by contractors, Fluorel finds uses in an oxygen umbilical tube, special eyepieces, boot soles and heels.

Various uses of similar copolymers developed by Du Pont and sold under its tradename, Viton, in nonflammable coatings and hoses were disclosed by Dale G. Sauers of MSC. As recently modified, these copolymers are self-extinguishing in 100% oxygen at pressures of 6.2 p.s.i.a., and in 60/40 oxygen/nitrogen at 16.5 p.s.i.a.

Office of Civil Defense Eighth Annual Fire Research Contractors Meeting, April 21–24, 1970. Asilomar, California

The agenda of this meeting, reproduced below, indicates the range of interest of this group. The ultimate objective of these studies is the amelioration of mass fire problems connected with nuclear blasts. Most of the work has a wider applicability in the area of urban fires. This broad spectrum of interests with long-term studies of complex problems has characterized this program. There appears to be a tendency to stress shorter-term objectives, which the reviewer thinks is unfortunate, but which probably is a sign of the times. Special emphasis was given in this meeting to problems of the interaction between blast and fire and its impact on shelter problems.

AGENDA

General Chairman—*Dr. Nevin Hiester, SRI*

Introduction	J. W. Kerr, OCD

Session 1. *Fire Defenses*

Fire Department Operations Analysis	H. Salzberg, IITRI
Mathematical Modeling of Fire Defenses	A. Takata, IITRI
Application of Fire Defense Systems Analysis	L. Eggleston, SwRI

Session 2. *Fire-Blast Environments*

Shelter Requirements in a Fire-Blast Environment	H. Sisson, OCD
Blast Evaluation of Existing Structures	Wiehle, SRI
Effects of Blast Effects on Fire Start and Spread	Goodale, URS
Development of Method for Assessment of Fire-Blast Vulnerability of Shelters	Avise, SSI

Session 3. *Evaluation of Fire Spread Models*

Fire Start Capabilities of Urban Nuclear Detonations	Bracciaventi, NASL
Evaluation of Ignition and Early Fire Spread Models	K. Miller, Dikewood
Evaluation of Fire Development Systems	Rodden, SRI

Session 4. *Fire Behavior*

Dynamic World War II Fire Effects	C. Miller, URS
Fire Spread and Behavior of Wild Land Fires	Tangren, USFS
Urban Burn Program	W. Christian, IITRI
Fire Spread in High Rise Buildings	A. Takata, IITRI
Firebrand Field Studies	H. Salzberg, IITRI

Session 5. *Shelter Fire Problems*

Survivability in Dual-Use Personnel Shelters under Fire Exposure due to Nuclear Weapons	Longinow, IITRI
Comparison of Total Hazards from Combined Effects to Shelterees in NFSS-Type Shelters	Avise, SSI
Slanting Basements in New Construction for Combined Nuclear Weapons Effects	Murphy, SRI
Heat and Humidity, Its Effects on Shelter Occupants	Pefley, University of Santa Clara

Session 6. *Fundamental Fire and Fire Modeling Research*

Origin and Properties of Fire Whirls	T. Waterman, IITRI
Fundamental Research in Limitation and Control of Fires	A. Lipska, SRI
Results of Electrical and Gas Models in Fire Research	Lee, SRI
Burning Scale Models of Camp Parks Buildings	S. Martin, SRI
Scaled Room Flashover	T. Waterman, IITRI
Committee on Fire Research Report	H. Hottel R.Fristrom, NAS-NRC.

Sessions 1 through 6 were held in the mornings. Each afternoon discussion sessions based on the morning presentations were held. At the last morning session, summaries were given followed by a summation of the total meeting by J. W. Kerr.

Three special sessions were held in the evening:

1. *The OCD Fire Research Program*—Mr. James W. Kerr, OCD, Chairman
   a) Present emphasis and future direction in OCD fire research
   b) Relationship of OCD fire research to the overall OCD research program
   c) OCD fire research and the operational concepts

d) Emergency Operations Simulation, Exercises, and Training—Harker, URS
e) Prototype Emergency Operations Planning—C. Rainey, SRI

2. *The Camp Parks Burns. The Australian Burns.*—Mr. Clayton P. Butler, SRI, Chairman
Movies of the Camp Parks Burns and general discussion. Movies, pictures, and discussion of the Australian Burns by Thomas Palmer, USFS, and others

3. *Fundamental Fire Research*—Mr. Stanley Martin, SRI, Chairman
Discussion of fundamental fire research problems by the Chairman and guests selected by him from among those present at the Meeting.

SUMMARIES

Office of Civil Defense Fire Research—James W. Kerr (OCD)

This section summarizes the evening session of 21 April, 1970, and incorporates the general conclusions growing out of several OCD-led discussion periods. The description of OCD research organization and the structuring of the program were covered in detail, but are not repeated herein because they appear in numerous readily available OCD documents.

Of particular interest, however, are the interfaces between research and other segments of OCD. Requirements for research support can be expressed by any operational element of the agency. Research outputs, however, are generally phased into implementation via Technical Services or Plans. Hardware items (e.g., radiacs, radio warming systems) are carried through the engineering and deployment phases by Technical Services. Software is handled by Plans, the point of origin of the Federal Civil Defense Guide, the "how to do it" book for state and local civil defense groups.

Within the OCD Research organization most fire studies are sponsored by Support Systems Division, with increasing involvement in recent years of the Shelter Research Division. In the distant past, a few threat studies have been sponsored by Systems Evaluation Division. Cooperation between Support Systems and Shelter is total, in theory as well as in fact. Scopes of work are discussed in detail prior to funding, and work progress of all work units is reviewed by both groups.

Philosophically, one could wish to fund all worthy efforts, but the budget squeeze has forced an ever more rigorous approach to selection of work to be sponsored. Some attention must be devoted to "quick fixes" for current problems. Some work pursues basic data or fundamental "truth," enhancing the state of knowledge in a given field. Some can be sponsored (especially in times of plenty) merely because of a knowing gleam in the eye of a credible scientist. But in all cases the watchword is "Relevance;" one must be able to ask "So what?" at the end of a program, and receive a reply that fits civil defense needs.

In an attempt to broaden our conception of relevance, this year's program includes two work units that are not "fire" research at all. As part of the support provided to Plans and Operations by Research, there is a continuing effort to provide a sound basis for viable plans. A series of scenarios was developed in connection with the Five City Study (see earlier Asilomar reports) and applied in an extension of that work. Findings to date reinforce exercise experience that indicates the understandable preoccupation of elected officials with their own electorate to the exclusion of mutual aid considerations. This work will be fed into the OCD training program when further developed.

In furtherance of the planning provisions of the Federal Civil Defense Guide, a series of prototype plans based on the Concept of Operations under Nuclear Attack are under development. These go into emergency plans in much greater depth than any prior efforts and may be expected to have major impact on Civil Defense disaster readiness in the next year or so.

Status Summary of Research on Fire Defenses—Lester A. Eggleston (Southwest Research Institute)

Three papers were presented in this opening session. Waterman (IITRI) presented the results of Salzberg's work on Fire Department Operations Analysis, Takata (IITRI) reported on Mathematical Modeling of Fire Defenses, and Eggleston summarized results to date on an application study of Fire Defense Systems Analysis principles to San Jose, California.

Earlier work by IITRI presented a review of manpower and water requirements for 134 fires in the Chicago Metropolitan Area. The current effort extended the geographical coverage to include a large and small city on both the east and west coasts, and confirmed the general relationships previously developed. When related to previous IITRI studies on what is actually required to extinguish fires of various sizes, it becomes clear that city fire departments in general are indoctrinated with the philosophy of using overwhelming forces against all fires. This would clearly be inappropriate in a nuclear attack fire situation where both skilled manpower and water supply resources would be limited and indicates a need for slanting all future training doctrine toward the conservation techniques which would be required.

Takata's development of a FIRE SPREAD-DEFENSE CODE to be combined with already existing IGNITION codes represents a major step forward in the analysis of nuclear fire conditions for various defense postures. For the San Jose attack scenario it was shown that self-help efforts could reduce the percentage of buildings destroyed after two hours from 6.3 percent to 1.3 percent when 14.1 percent of the population were participating. Since other studies, notably those by Moll of SRI, have shown that simple thermal hardening is an extremely effective fire defense, it would appear that the next logical step would be an appropriate modification to the IGNITION code to consider the reduced ignition probabilities made possible. When combined with the new FIRE SPREAD-DEFENSE CODE, an excellent overall analysis could then be obtained, especially at such time when corrections could be made for the extent of blast damage to structures now being studied by Wiehle of SRI.

Eggleston's analyses of applying the hypothetical fire defense system developed in FIRE DEFENSE SYSTEMS ANALYSIS to an assumed attack at San Jose emphasized the need for a common sense defense approach, using techniques which would be acceptable to both the fire services and the populations in general even without a high degree of emergency motivation. A thin, aluminum-coated mylar film material was exhibited as a useful window covering material for thermal hardening which was sufficiently transparent for normal vision, yet could screen out 85 percent of external radiation, and reduce air conditioning loads in peacetime applications.

The study to date supported an optimistic view of the fire defense which would result from application of the hypothesized system at San Jose. It now appears that unless a building was so heavily damaged by blast that it became a total loss, it probably would not be destroyed by fire and further, the probability of ignitions in structures suffering major damage would be reduced to a point which would minimize or eliminate the conflagration hazard in high overpressure areas. The original step-by-step analysis of conditions in zones of increasing overpressure is now being restudied to more carefully consider the effects of blast damage to wood frame structures as pointed out by Wiehle and for the time history of thermal pulse and blast wave as suggested by Martin.

Shelter Fire Problems—George Sisson (OCD)

In terms of fire-blast environments as related to the survival of people, the discussants agreed that characteristic shelter postures should be considered. It was agreed that the following shelter postures or modes should be discussed as separate problems.

A. Residential Mode
B. National Fallout Shelter Survey (NFSS Mode)
C. Blast-Slanted Shelter Mode.

A. Residential Mode

For people who are sheltered in land use classes which are primarily one- and two-family residences, estimates are required for initial ignitions at varying ranges, for the subsequent response of residences to blast and possible redistribution of the fuel, and for the types of fires which are likely to develop in the damaged shelter mode. Experimental work aimed at this problem should be performed by studying burning characteristics of residential fuel loads distributed over variable areas to match conditions at various ranges from a weapon. Fire-fighting requirements for survivors in residences could then be outlined for conditions expected to prevail at discrete overpressure regimes.

B. National Fallout Shelter Survey (NFSS) Mode

People sheltered in the NFSS mode are generally sheltered in the basements and on upper stories of buildings characterized by heavy floors and walls where good fallout protection is likely to be found. Here again, it is necessary to define the sequence of events following detonation of the weapon and the resultant environment in which the survivors find themselves. The buildings will generally be load-bearing or framed structures, and will generally be found in heavily built-up areas where the mass fire hazard may or may not be great. At ranges where the thermal pulse is sufficiently intense to create fires, the blast overpressures will generally be great enough to dislodge shelterees and combustibles to varying degrees. Survivors in shelter buildings which contain fires should organize to extinguish fires as rapidly as possible after attack and to attempt to prevent fires in immediately adjacent buildings. Contingency plans must be developed to attempt to escape to less damaged and non-burning areas in the event the fire problem in the vicinity of the shelters becomes uncontrollable. People surviving fire and blast on upper stories may still be subjected to uninhabitable smoke concentrations, a region in which the state-of-the-art is poor. While people should preferentially take shelter in basements to the maximum extent possible to maximize protection against thermal pulse and blast, this may complicate the fire fighting on upper stories of buildings which may constitute the best fallout protection immediately post detonation. The extent to which this complicates fire fighting has not been evaluated.

Concern was expressed that for fires of great area extent, temperature conditions throughout the city are poorly understood. It was agreed that the location of blast dislodged debris and the burning characteristics of such debris was also poorly understood.

C. Blast-Slanted Shelter Mode

Shelterees housed in blast-slanted shelters would be those who occupied basements of buildings, which, when designed, would be provided with a strengthened floor slab over the basement. Special precautions would be taken to minimize fire hazards within the shelter facility and to select those facilities for slanting which were sited relatively fire-hazard free environments. It is presumed that such development of a national shelter system in future years would be accompanied by a shelter management training program and an organization which would contain provisions to exercise countermeasures during and after attack to maximize survival. Fire-fighting teams would be organized and fire-fighting tools would be stocked as part of the shelter supplies. Provisions would be included for setting up and operating necessary stocked ventilating equipment. Fire research problems associated with the development of a blast-slanted shelter system would be to predict the distribution of blast produced array of combustibles, the extent to which ignitions occurred, and the probable burning and noxious gas productions of such fires. Procedures for such should be developed for predicting the location of fresh air intakes and for predicting the quality of the intake air.

Status Summary of Research on the Effect of Blast on the Fire Environment in Urban Areas due to Nuclear Weapon Explosions—Thomas Goodale (URS)

Research on the effects on urban structures of the blast waves produced by nuclear weapons illustrated the large effect of blast on the ultimate nature and distribution of fuel available to fires in such areas. Such changes in the distribution of fuels must have their principal effect on fire spread and other late-time effects.

In addition, blast can be expected to affect the occurrence of primary ignitions early in time, owing to its effect in either extinguishing primary fires due to aerodynamic effects, or of spreading ignition, in some circumstances, due to translation and spread of ignited kindling fuels by the blast wave.

The effect of blast on the fire environment in civil defense has been largely neglected heretofore, and the interactions characterized above are generally unknown as to their nature and extent. It can be expected that conditions will be complicated and exacerbated in the case of weapons of megaton TNT-equivalence compared to weapons of the kiloton range to which the sparse data presently available regarding blast-fire interactions correspond. The megaton-yield weapons provide much higher total dynamic pressure impulse at a given overpressure than do smaller weapons owing to the longer time duration of positive particle velocity following their shock fronts. The blast waves of these weapons at a given overpressure can therefore be expected to translate and redistribute shattered structures more completely and to greater translational distances than do the smaller weapons. Furthermore, the incidence of primary ignitions by the thermal pulse of weapons in the megaton range is complicated by the increased duration of the pulse. In many conditions in the blast overpressure range of interest to civil defense, a significant portion of the total energy radiated in the thermal pulse will arrive after passage of the blast wave, so that the possibility of primary ignitions in the redistributed fuel mass must be considered.

Owing to the complexity of the blast-fire interaction in relation to the resources presently available for its investigation, it is important that the part of the problem having greatest potential in improving the effectiveness of shelter survival and recovery operations of civil defense should be investigated first. In their initial investigation of the subject (URS 705-5, Effects of Air Blast on Urban Fire Response, May 1969), S. B. Martin *et al.* analyzed the interactions possible in a wide variety of blast and fire responses, and concluded that the effect of blast on the incidence of primary fires in urban interiors would probably constitute the most important influence of blast on the fire environment. In their investigation of this subject, they studied the velocities and structure of air flow induced in rooms due to passage through windows of the blast waves themselves and of the heated compressed air behind the shock that would be reflected from exterior wall areas adjacent to the window. The effects of these flows in translating room contents was investigated.

In the continuation of this investigation currently in progress,* the interaction of blast-induced air flows with primary fires ignited in typical room furnishings will be explored.

In addition to the behavior of ignited material and room contents due to blast, consideration is being given to cases in which certain elements of the room itself are allowed to translate, viz., the wall of the room opposite the exterior wall on which the blast is incident. This wall will be made frangible in one configuration to simulate the structural behavior of a relatively weak interior partition opposite the exterior wall through which the flow enters.

The results of these initial experiments can hardly fail to be highly instructive, since virtually nothing is known at present of the effects of blast on primary ignition. Any claim to a working insight into the effect of blast on the incidence of primary ignitions, however, can only result from continued investigation of the effect on primary ignitions of more comprehensive blast-induced failure modes.

In addition to the question of the early-time effects of blast on primary ignitions, little is presently known of the changes in the fire environment brought about by blast-induced redistribution of fuels. Where analysis of the shelter capability of high-rise buildings have indicated the likelihood that much of their contents on each floor, including light partition walls will be translated into adjacent streets, the question arises as to the fire environment presented by the removed material, and whether shelters in the vicinity would be made uninhabitable due to such fires. Similarly, the question of whether the breakup and redistribution of suburban residential buildings over the area intervening between them would constitute a fire environment either more or less hazardous and difficult to control than that which would obtain in the same buildings intact, cannot presently be answered conclusively.

* These investigations are being conducted experimentally at full-scale in the URS Shock Tunnel Facility.

Fire Behavior—Arthur Takata (IITRI)

This session covers five papers that deal with the development and spread of fire in areas ranging from forests to urban areas. Experimental as well as analytical studies are included.

The first paper is titled "Dynamic World War II Fire Effects" and involves the synthesis of data collected from World War II fires in Hamburg. During the course of the study, data will be documented indicating the fire conditions, and the effectiveness of fire defenses, as well as constraints on fire fighting, escape, and survival. Very valuable data are available with which to serve as a real-world check on present descriptions of various phenomena, as well as to guide the formulation of countermeasures. Before data are selected efforts should be made to define those data needed by the user to develop a complete understanding of the phenomena in question. For example, data describing the number of fires fought and extinguished would serve a much more meaningful purpose if complemented by data describing the number of fire fighters per building, building density, description of buildings and fires, and how rapidly the fire fighters commence to fight fires. Also, information describing the spread of fire between buildings would be much more meaningful if accompanied with descriptions of the buildings and the spacings between buildings.

The second paper is termed "Fire Spread and Behavior Data from Wildland Fires" and has as its purpose the development of a data bank of information from free burning fires. These data include information describing the character of the fire, weather, topography, fuel, spotting, and rate of spread of the fire front.

Data procurement has always presented a problem with fires and is a difficult task with forest fires because of the uncontrolled and unscheduled nature of the fires. Spotting and fire spread determinations are best made from aerial observations. To provide an understanding of the rate of fire spread, data should also be provided for the rate of fuel consumption per unit length of fire front.

The third paper is titled "Urban Burns—Full-Scale Field Studies" and has as its objective the collection of various data from the burning of eight structures consisting of five frame farmhouses, one masonry wood-joint residence, one tavern, and one gas station. Data collected included the rate of fire spread within the structures, radiant intensities outside the fires, pressures generated under roofs, deposition of brands, and gas concentrations in basements. Of particular interest is that the radiation was sufficiently intense in one of the eight tests to produce a spontaneous ignition at 50 feet. Also, firebrands were deposited as far as 435 feet from the fires under conditions of light wind.

While considerable information was acquired in these tests, certain additional information should be procured in future tests. First, sufficient radiometer coverage should be provided to insure a comprehensive description of the irradiance at various directions and distances from the fires. Also, provisions should be provided to allow a determination of pilot ignitions by the radiation. This is particularly important because the energies for pilot ignition are only about half those for spontaneous ignition.

Another problem has to do with the deposition of firebrands. Descriptions of the number and sizes of brands have always posed a problem because of frequent breakup of brands on impact with the ground. The difficulty arises in attempting to decide whether multiple holes in polyethylene sheets are caused by several brands or by fragments from a single brand. An incorrect interpretation can lead to appreciable errors in the probabilities of fire spread.

The fourth paper is titled "Fire Spread in High-Density, High-Rise Buildings" and is concerned with the development of a computer routine to predict the spread of fire in high-rise buildings and its consequences on the street environment. Preliminary results indicate that a large fraction of the fires will be started in the upper floors and cause very intense fires in the first hours following a nuclear detonation. Most of the lower floors will be free of fire at least for the first few hours provided the lower floors are not ignited by burning debris thrown into the streets by the blast.

Two spread phenomena are very poorly understood, namely, fire spread from window to window, and fire spread within fire-resistive structures that are compartmented and contain appreciable fuel loads. Another is the possibility of debris fires in the streets, and its effect on the buildings and on the occupants of shelters.

The fifth and last paper is titled "Firebrand Field Studies" and involves the collection of firebrand data from IITRI field burns, reports of accidental fires and answers to questionnaires. While considerable data have been acquired to describe the formation, sizes, and transport of firebrands, existing data are inadequate for estimating the disposition of firebrands. Also, there is information regarding the ability of firebrands to ignite host materials. However, the weakest link in predicting fire starts by firebrands is the lack of information regarding the effect of air currents on the trajectories of firebrands as they near buildings and the likelihood of firebrands landing on host materials capable of initiating a building fire. At present, available data permits only very crude estimates of the probabilities of fire spread by brands.

Evaluation of Ignition and Fire Spread Models—Keith Miller (Dikewood)

At present, OCD is proprietor of four models treating ignitions caused by nuclear attack on urban areas. Three of these ignition models are associated with models of the spread of fire from the buildings initially ignited. Many details of these models have been reported at this conference by Dikewood and SRI.

The results predicted by the models, under identical conditions, differ very markedly. This is true both for ignition and for fire spread. In addition to reporting and explaining these differences, and selecting the best of the models, it is hoped that Dikewood and SRI will be able to:

1. Specify the most nearly correct values for the various parameters which are "known" and
2. Point out the areas where the models are the most sensitive to relatively "unknown" parameters, i.e., to suggest the most fruitful areas for further research.

As more and better data become available, inputs to the models must be changed and, in some cases, modifications to procedures used by the models may be indicated. We, therefore, reaffirm the goal of producing a model capable of being readily adapted to the changes in inputs, procedures, weapons, and attacks which result from various developments.

A few *very* general comments may be of some value:

It is suggested that progress in this area could be accelerated by the use of better reporting procedures. Obscure programming and fragmentary documentation do more than shorten final reports. They make evaluation, use, and even understanding, of the models by other investigators very difficult, and thus lead to wasteful duplication of effort. It would perhaps be desirable for OCD to establish a library of the computer codes whose development they have sponsored, along with complete guides to their use, for the convenience of all those involved in fire research.

It would appear that extended concentration on the Five City Studies burst may have resulted in rather incomplete, and therefore misleading, ideas in the minds of many concerning the relationship between blast effects radii and thermal effects radii. This may be gradually overcome by including treatments of a variety of yields and burst conditions in future published threat analyses of all kinds.

Finally, it should be stated once more that much of the lack of agreement between the models may be traced to the condition of the data base. Uncertainty is *not* limited to the area of blast-fire interactions. Each of the pertinent research areas contains large unsolved problems. Until certain of these problems *are* solved, no model, present or future, can make predictions having a reasonable confidence level.

Status Summary of Research on Fundamental Fire and Fire Modeling—Anne E. Lipska (SRI)

The work units in this session range from investigations of the basic understanding of the pyrolysis processes of the cellulose molecule to studies of mass fire behavior.

The study of the isothermal pyrolysis of cellulose is an extension of last year's work and focuses primarily on performance of additional checks on the Parker-Lipska model of decomposition of cellulose. The results of the present investigations were in good support of the model.

Since the increase of char and rate of degradation in cellulose, due to flame-retardant treatment, can now be predicted quantitatively and therefore aid in the selection of more effective flame retardants, emphasis in the future work should be placed on the concentration effect of retardant loading on ignition hazards of flammable degradation products resulting from the treatment, as well as possible production of toxic products. Questions of whether or not the retardant-treated material ignites at low irradiance levels, and the treatment suppresses glowing ignition and/or flame spread along the item, should also be considered when selecting the most efficacious retardant.

Results of the investigations on scaled-room flashover established the minimum model size that can be related to full-size room conditions which lead to room flashover. Future plans are directed toward studying the effects of varying the many room and fire parameters on the development of conditions supporting room flashover. In addition to the parameters already considered, substantial effort should be placed on the mechanism of flame spread from item to item which would eventually lead to room flashover. Synergistic effects of various types of furniture on time of flashover should also be investigated. Whether or not the time of flashover depends upon the location of the ignitor should also be established.

The first year's effort of work on burning scale models of Camp Parks buildings (sectioned Corpsmen Quarters) centered on detailed studies of fire spread from room to room in actual buildings both at Camp Parks and at Pleasanton, and 1/16-scale models of the sections. Results were reported in terms of total energy release rate, air velocity, thermal radiation, and concentrations of CO, CO_2, and O_2 inside the buildings as well as in the basement and/or shelter area. Excellent correlation was obtained between the data collected from the burning buildings and the scaled models. Future work is directed toward establishing the criteria that lead toward fire spread between buildings as well as 1/6-scale models. Both the scale models and the full-size buildings will be fully instrumented for new tests as well as replications to confirm data that have already been collected. In order to take advantage of the results from all previous burns, it is essential to establish scaling relationships from which valid predictions of fire behavior may be made. Therefore, a mathematical basis for scaling of buildings and parameters affecting burning and interactions between structures should be emphasized.

The work on the origin and properties of fire whirls is completed. The purpose of this study was to determine the origin of the vertical vorticity to sustain the fire whirls. The results indicated that the largest source of vertical vorticity is the upward bending of the horizontal vorticity to the ambient wind. The magnitude and direction of the vorticity agreed with the pattern of circulation found in the wind speed measurements of project Flambeau. These findings should be applied to scale models of large-area fires where conditions leading to the development of fire whirls may be duplicated.

The results of the work done on electrical and gas models in fire research indicated that the modeling technique used in this investigation can be successfully applied to studies involving the low-elevation, transient-flow environment in large-size fires, and thereby contribute to the prediction of subsequent fire spread around and within the fire-affected area. Good correlation was shown between the prototype velocity and temperature histories obtained from the near-street-level environment in the Flambeau fires of June 1966 and September 1967 and the data collected from a combination of laboratory-size electrical and gas models. Future work will compare air flow around burning small model structures with the data obtained from the Camp Parks burns. A simple wind source will be selected to study the influence of wind on large-area fires. In addition, the possibility for wind-generated fire whirls will be investigated with the gas model in the wind source.

Australian Burns (*Operation Euroka*)—T. Y. Palmer (U.S. Forest Service).
Camp Parks Burns—Clayton Butler (SRI)

This evening session began with a discussion and picture of the mass fire experiment in Australia, called *Operation Euroka.*

Preliminary results of this fire are:

1. Wind inflow and burning rate data show that experimental values deviate considerably from values predicted by model theory.
2. Meteorological conditions of low relative humidity and high ambient wind speed are characteristic of an explosive fire condition.
3. Subrefraction, or a backward tilting of the wave fronts of radio signals transmitted through the high temperature region can adversely affect radio communication.
4. Life hazards due to radiant heat and high air temperatures exceeded thresholds in the central areas of the fire. Personnel housed in a bunker near the center would have survived the heat, but would have been in serious trouble with CO concentrations, even many hours after active burning.
5. The following constants were determined for the *Euroka* fire:

a. Semiangle of convective column cone	14°
b. Ratio of pinch height to fire radius	0.84
c. Ratio of pinch radius to fire radius	0.38
d. Projected column radius to fire radius	0.18
e. Constant relating to inflow to energy release	1.25 m/sec
f. Reynolds number	1.4×10^8
g. Logarithmic wind velocity profile	0.2
h. Velocity deviation to average velocity	0.12 before
	70.25 during

The second part of the evening session was a showing of a partially edited movie depicting the activities of the fire research people and the firemen at Camp Parks during some of the building burns. This film is designed for showing to fire departments who assisted at each burn. It portrays the installation of instruments, the recording instrument trailer, and how gas samples, for example, are measured during burning.

The purpose of this film is to show one phase of fire research involving the burning of actual buildings, the extensive preparation, how the data are acquired, and how they are interpreted. A running commentary accompanies the movie so that it can be shown without one of the investigators to introduce the subject.

Fundamental Fire Research—Stanley B. Martin (SRI)

The program consisted of three presentations. The first two dealt with carbon formation in combustion, and the third, with mechanisms of ignition. These topics were selected because they seemed to have the greatest relevance to OCD's first line of defense—the avoidance of initial fires set by the thermal radiation of nuclear detonations. Carbon-particle smoke screens have been seriously considered for some time as a thermal radiation countermeasure to protect urban areas. Their costs, however, are high; and more efficient conversion of hydrocarbons to carbon would make implementation of the concept more attractive economically. Very little theoretical or experimental background has existed until recently from which the development of more efficient smoke generators could proceed. Similarily, the treatment of kindling fuels to make them less suceptible to ignition is well recognized as a countermeasure to primary fire vulnerability, but the development of suitable treatment is hampered by a lack of understanding of the fundamental mechanisms of the ignition process.

Mr. Thomas Goodale (URS) discussed his attempts to improve the efficiency of carbon production in the pool burning of hydrocarbon through addition of catalytic agents to the hydrocarbon source and oxygen to the air. Substantial increases were obtained in some situations, but efficiencies of about 30 percent appear to be the practical limit, and such efficiencies are obtainable (or nearly so) from the common unsaturated hydrocarbons without treatment. Dr. Alvin Gordon (Naval Weapons Center) reviewed his work on carbon forming reactions in flames, lending additional insight into the fundamental processes and their limitations. There is apparently little reason to be hopeful that substantial improvements in carbon formation can be obtained from free-diffusional burning of hydrocarbons, and other methods that have been conceptualized are prohibitively costly. Therefore, the system as it exists is a near-optimal one.

Mr. Norman Alvares (SRI) presented experimental data he has taken on ignition of thermally irradiated cellulose in various atmospheres, and attempted a preliminary explanation of the dependence of ignition times and temperature on total pressure, oxygen concentration, and diluent substitution. He showed that the dependence of ignition thresholds on these atmospheric variables is reasonably consistent with calculation based on a simplified model of thermal autoignition and is totally incompatible with the previously held notion that ignition is triggered by the sudden appearance of reactive pyrolysis products. Due to the oversimplified nature of the thermal autoignition model, any conclusions in support of thermal autoignition must be regarded as quite tentative. Need for further work along these lines is indicated.

Western States Section of The Combustion Institute, April 20 and 21, 1970 University of California, Berkeley, California

The twentieth meeting of the Western States Section of the Combustion Institute met at the Alumni House for two warm sunny days on the Berkeley campus of the University of California. The overall program of the meeting strongly indicated the continuing importance of problems related to atmospheric pollution of the environment. Most of the papers dealing with air pollution were concerned with the importance of nitric oxide production as a major contributor to the eventual formation of photochemical smog. There seemed to be general agreement that much work is still needed in this area. Other papers dealing with both heterogeneous and homogeneous reactions were presented.

The first morning session was conducted by Professor E. S. Starkman who discussed the general problems in air pollution, noting with interest the tear gases used in very recent Berkeley disturbances. John W. Bjerklie (Mechanical Technology Inc.) then opened the meeting with a discussion of a turbo-Rankine accessory system operated with a conventional engine using 10% recirculation and an afterburner system ("An Automotive Accessory Power System Incorporating Emission Clean-Up," WSCI-70-1). Recirculation maintains reasonable NO levels and afterburning of CO and unburned hydrocarbons is used with a regenerating unit to power auto accessories. Design requirements for the reactor are found using a flame speed model which considers both kinetic and diffusion controlled ignition. Fuel economy and power requirements were shown to be best served by using a premixed ignition system with a minimum of excess air in the accessory power unit. The system may also be capable of lowering automotive emissions to 10 ppm UHC, 0.2% CO, 150 ppm NO with little fuel penalty.

Dean Hammond (Purdue University) presented preliminary work on combustor modeling which may eventually become very useful in predicting the chemical kinetics and air pollution characteristics of gas turbine engines ("A Preliminary Investigation of Gas Turbine Combustor Modelling," WSCI-70-2, Dean C. Hammond, Jr. and Arthur M. Mellor). It was noted that both mixing and chemical phenomena must be considered in the modeling procedure. Russian work, incorporating turbulent flame modeling and turbulent eddy theories, was discussed but was not used in the present model. Instead, a system of perfectly stirred reactors along with plug flow reactors are used to model the primary and secondary zones. The model considers air addition in the secondary zone and recirculation in the primary zone. Future work would incorporate chemical kinetics into the model.

Experimental work is also underway as a means of determining the utility of the physical model.

H. K. Newhall (University of Wisconsin) then discussed experimental work in flames representative of those in automotive cylinders ("Formation Kinetics of Nitric Oxide in High Pressure Flames," WSCI-70-3, S. M. Shahed and H. H. Newhall). Spectral ultraviolet absorption techniques are used to follow NO formation in a flat flame front propagating through a high pressure combustor chamber in a hydrogen-air mixture. It was found that in fuel lean flames, NO formation occurs primarily in the post flame gases. The Zeldovich mechanism adequately explains the production of NO at these conditions. However, in fuel-rich flames, there is very rapid initial formation of NO at the flame front and equilibrium concentrations are quickly achieved. The Zeldovich mechanism cannot explain this behavior and possible explanations for the discrepancy were given.

L. Caretto and G. Johnson (University of California, Berkeley) presented experimental and theoretical work concerned with oxidation of carbon monoxide in engines ("The Kinetics of CO Oxidation in Reciprocating Engine Cylinders," WSCI-70-4, G. L. Johnson, L. S. Caretto, and E. S. Starkman). CO and CO_2 concentrations versus time were measured during a single engine stroke in a one-cylinder engine. Samples were obtained via a hydraulically actuated sampling valve. Theoretical calculations using a reasonable kinetic scheme did not give good correlation with experiments. However, hydrogen-oxygen equilibrium or partial equilibrium of atomic species were assumed. In addition, there was general agreement that the sampling valve techniques could easily lead to large errors in concentrations of CO and/or CO_2.

The afternoon session was conducted by M. Gerstein. The first two papers considered pollution from stationary sources. B. P. Breen (Dynamic Science) presented an overall engineering approach for nitric oxide control in combustion processes ("Nitric Oxide Reduction by Controlled Combustion Process," WSCI-70-5, A. W. Bell, N. Bayard de Volo, B. P. Breen). Experience with large power plants has indicated that combustion control can reduce the NO levels from 75–90%. In addition this can be attained with little or no hardware changes by using programmed phasing of fuel/air flows in the plants. Simple design controls make use of reduced air preheat, two stage combustion and mixing techniques, off-stoichiometric combustion, and, most importantly, recirculation of burnt gases. These techniques are proposed for control of NO in gas turbines as well.

L. L. Acton (General Dynamics) discussed an infrared absorption technique for remote sampling of smokestack effluents ("New Methods of Measuring Smokestack Effluent Gases," WSCI-70-6, L. L. Acton, C. B. Ludwig, M. L. Streiff). The many problems connected with remote sampling were presented along with previous attempts at a solution. The infrared correlation technique presented has certain advantages over other methods but the temperature of the smokestack plume and self-emission of the atmosphere must be known. Preliminary results with SO_2 show that the system may be feasible, but the present developments are not conclusive In spite of the difficulties however, this method offers the possibility of real time measurement of all important pollutant species using perhaps the least complex system of remote measurement.

David T. Pratt (Washington State University) discussed a method for obtaining theoretical distributions of residence times in potential combustion systems ("The Distribution of Residence Times in a Confined Round Jet," WSCI-70-7, David T.

Pratt). Mass entrainment and recirculation models are considered to show that velocity field measurements can be used to predict residence times in combustion systems. A method of characteristics solution leads to a "characteristic delay time" which denotes the level of stirring in a combustion system. This parameter is a continuous function of the velocity, temperature, and concentration fields. On the macroscopic scale, integration of the proposed microscopic equations leads to a continuous parameter shift between perfectly stirred and plug flow reactors. The application of this method to kinetics calculations was questioned, however.

The afternoon session was concluded with a presentation by James L. Hodges (Stevens Institute of Technology) of work related to the measuring of NO kinetics in a simulated engine cylinder using a quiescent fuel/air igniting mixture. ("Nitric Oxide Kinetics during Rapid Expansion of Octane-Air Combustion Products," WSCI-70-8, James L. Hodges and Robert F. McAlevy, III.) Although time resolved data have not yet been obtained, the ultraviolet absorption technique for measurement of NO concentration in this system may be very useful despite data scattering problems and interference from the O_2 Schumann-Runge bands. The analogue combustion chamber gives reproducible pressure traces comparable to those from an engine cylinder. Preliminary results verify that freezing of NO is very rapid in the expansion stroke.

The afternoon session ended with a discussion of the need for better kinetic data in NO systems. It was pointed out that our knowledge of pure NO kinetics is not as good as one would like to think. The use of various equilibrium assumptions was also questioned.

Dr. A. Gordon led the second morning session which dealt with miscellaneous topics related to heterogeneous and homogeneous kinetics. R. H. Knipe (Naval Weapons Center, China Lake) opened the session with a discussion of certain proposed models for boron particle combustion ("Condensed Phase Effects in the Combustion of Boron Particles," WSCI-70-9, R. H. Knipe). The models use the familiar diffusion controlling mechanisms with certain changes in order to consider the qualitative influence of the condensed phase product. It was found sufficient to consider just two influences of the condensed phase: product condensation in a zone detached from the surface, and a rate controlling oxide film on the particle surface. Models with and without dissociation were considered (low temperature and equilibrium models). The low temperature model indicates a lower limit of oxygen concentration below which steady-state combustion will not occur. This limit is in agreement with available experimental evidence. There are certain qualitative consistencies between theory and experiment at high oxidizer concentrations; however, the equilibrium model offers no clear-cut predictive value as yet.

R. P. Wilson, Jr. (University of California, San Diego) then presented a review of the possible uses of holography in heterogeneous combustion phenomena ("Observing Heterogeneous Combustion by Motion-Picture Holography: Some Prospects and Limitations," WSCI-70-10, R. P. Wilson, Jr.). Evidence indicates that spatial, time, and size resolution of condensed particles in various combustion phenomena could be studied using motion picture holography. There are problems connected with the control of intermittant light beams and recording of successive holograms at high speeds, however. Although field depth is no problem, image blur is easily registered if there is any relative motion between the light source and the recording emulsion. It appears that the primary limitation for the use of holography in combustion processes is connected with rapid density changes in the field which causes degradation of the pictures. The particles must be over 2μ in size to make this process useful.

Robert A. Rhein (JPL) then discussed the reaction between OF_2 and B_2H_6. ("The Reaction between Oxygen Difluoride and Diborane: II. The Kinetics and a Proposed Mechanism," WSCI-70-11, Robert A. Rhein). The reaction was studied at temperatures ranging from 300°–330°K at initial partial pressures of 1–30 torr for B_2H_6, 5–40 torr for OF_2. The initial overall rates of BF_3, B_2H_6, OF_2 were found using an infrared transmittance system. A mechanism was then proposed which gave results comparable to the experimental data. The hypothetical mechanism makes use of a two-step system involving intermediate species and complicated polymers of boron and fluorine.

The final paper was presented by W. J. McLean (University of California, Berkeley, "Chemical Kinetics in Free Jet Expansions," WSCI-70-12, W. J. McLean and R. F. Sawyer). The presentation was concerned with the effect of recombination reactions in free jet expansions. This information is very important in the design of molecular beam inlets for mass spectrometers where the spacing between nozzles and/or skimmers is dependent on the quenching characteristics in the expansion. The integrity of the sample can be maintained if the spacing between elements of the mass spectrometer can be varied to conform with the species considered. The systems H_2–H and H_2–F_2 are considered in the present paper. It was found that, for both systems, the degree of reaction in the free jet expansion decreases with decreasing hole size. However, it was indicated that there is a lower limit to hole size due to viscosity effects.

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Fire Research Abstracts and Reviews

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FIRE RESEARCH ABSTRACTS AND REVIEWS

Robert M. Fristrom, Editor

Geraldine Fristrom, Associate Editor

The Committee on Fire Research

FIRE RESEARCH ABSTRACTS AND REVIEWS will abstract papers published in scientific journals, progress reports of sponsored research, patents, and research reports from technical laboratories. At intervals, reviews on subjects of particular importance will be published. The coverage will be limited to articles of significance in fire research, centered on the quantitative understanding of fire and its spread.

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FOREWORD

The recent news of two fire disasters, one in California and the other in France, has brutally reminded the public of the fire problem. These fires are only the most recent recurrence of two types of holocausts. In almost every decade, bad fire weather, poor housekeeping, and shake roofs combine to produce disastrous California fires. The French dance hall fire is reminiscent of the notorious Coconut Grove fire in Boston.

The readership of this journal needs no reminder of the presence of fire dangers. Almost the only good to be salvaged from such disasters is re-aroused public awareness, reminding people that it can happen here, and urging greater effort in finding remedies for obvious fire hazards. We can hope that some improvement in fire-prevention habits, laws, and enforcement may result from such sad affairs.

This issue begins with a most interesting historical article on Voltaire's views on fire, by Dr. George Agoston, of UNESCO, Paris, France. Although the ideas are principally of historical interest, it is refreshing to see fire problems through other eyes. Voltaire's view on extinguishment of fire by water—that the water separates fire from its air supply—is quite close to some modern thinking.

It is your editor's pleasure to introduce the new associate editor on our masthead, Mrs. Fristrom, who was part of the original team that Dr. Berl, our founding editor, brought together to initiate FRAR. Through the years she has had the responsibility for initial screening of articles for abstracting and review. Her responsibility will now be extended into general editorial work.

Robert M. Fristrom, *Editor*

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VOLTAIRE ON THE CHARACTERISTICS OF FIRE AND ITS PROPAGATION*

GEORGE A. AGOSTON

Paris, France

Voltaire's Entry into Science

The story of Voltaire's interest in science[1–7] begins in 1726, when, acclaimed as a poet by the enlightened but menaced by the functionaries in Paris, he went in exile to England. Three years later, at age 35, he returned to Paris, a champion of Newtonianism and a militant opponent of Cartesianism, which was still dominant in French science. Soon thereafter, he published his "Lettres philosophiques" (1734), a collection of popular, laudatory accounts on Francis Bacon, Locke, Newton, English literature and English institutions, ending with a critical essay on Pascal. The book aroused the anger of the French authorities and the edition was ordered to be burned. To escape arrest, he left Paris and soon took up residence in Cirey near the German border, at the château of his friend Mme. Du Châtelet, the beginning of an affair that ended with her tragic death in 1749.

Mme. Du Châtelet had been very well tutored not only in languages and philosophy but also in physics and mathematics (the latter by Maupertuis and Clairaut). She undoubtedly gave Voltaire much assistance in 1736–1737 when he was immersed in studies in physics and mathematics and in writing his "Éléments de la philosophie de Newton,"[6] a book directed to the French public popularizing metaphysics, optics, and the law of gravitation.

A Prize Offered by the Académie

In the spring of 1737, Voltaire began work on a paper in a competition sponsored by the Académie Royale des Sciences. For that year, the topic of the competition was the characteristics of fire and its propagation.[8] The competition was open to all except members of the Académie. The precise reason for Voltaire's interest does not seem to be known. Libby suggests in her book that he had ambitions to enter the Académie and considered that a successful paper would aid him to this end.[3]

About 30 papers were submitted,[9] but Voltaire's was not among those selected by the judges. The prize of 2,500 French pounds (about $2,500 today[10]) was divided among three winners: the Swiss mathematician, Leonhard Euler, the jesuit priest, Lozeran de Fiesc, and the Marquis de Créqui, a lieutenant general. After receiving the disappointing news, Mme. Du Châtelet revealed to Voltaire that she, too, had prepared and submitted a paper. Later, in a letter to Maupertuis (D1528, June 1738)[10] she explained that she had been so stimulated by Voltaire's

* The authorization to consult the Archives of the Académie des Sciences, 23 Quai Conti, 75-Paris 6, and the assistance given by the Archives staff are gratefully appreciated.

work on combustion, that she had not been able to restrain herself from writing her own thoughts on the subject, but in secret for she had feared that it might displease him.

The three selected papers followed by those submitted by Mme. Du Châtelet and Voltaire were published by the Académie in 1752.[11,12] The latter two appear anonymously, because the policy was to name only the successful contestants. The Académie stated that the two papers were published in response to the request by their authors. (This request can be traced in an interesting series of letters in May and June, 1738.[10]) The Académie added that, while it did not find their concepts of fire acceptable, their papers appeared to be the best from the standpoint both of their apparently extensive reading and familiarity with the great works in physics and of the many facts and views presented.[11]

During the public announcement of the awards, 16 April 1738, it was stated that the Académie felt the need to propose oftentimes subjects for the prize that were very difficult and little understood. It was added that the topic of fire was perhaps one of these and, consequently, that only discussions of hypothetical "systems" could be expected. Several of this type had been received, but none was found to present a fully satisfactory explanation of fire. It was decided to divide the award equally without distinction among three contestants whose papers it had considered the best and who had employed completely different approaches.[13]

The Winning Papers

Euler's paper* "Dissertatio de Inge"[11] describes fire as a fluid filling the pores of all matter. Some of the fire is held under pressure in tiny cells. The fluid fire can reveal itself in two ways. When two bodies of different temperature are brought into contact, fire flows from the pores of the warmer into the pores of the colder, a change that we sense and call heat. If, however, a body is subjected to more violent treatment, e.g., a blow, friction, exposure to a spark or flame, then combustion occurs. In the area of ignition, cell walls are broken releasing entrapped fire fluid. Furious motion is produced in the pores causing more cells to break. The structure of burning matter is destroyed by this motion, progressively releasing particles to the air and yielding an incombustible residue of ash and salt. Combustibility variations from one substance to another are explained by differences in pore and cell structure.

Euler's paper concludes with a brief presentation of thoughts on the speed of sound in elastic media. Noting Newton's expression for the speed of sound $(p/\rho)^{1/2}$ where p is gas pressure and ρ is gas density, he proposed another, also incorrect, without derivation.[15] Euler attempted to solve the problem again in 1750, but unsuccessfully.[16] Then La Grange, on a new attempt in 1786, only verified Newton's equation.[17] The correct expression $(p\gamma/\rho)^{1/2}$ containing the ratio of specific heats was finally presented by La Place in 1816.[16]

Fiesc's concept of fire, presented in his "Discours,"[11] is rather elaborate. Fire is characterized by the presence of a mixture of volatile salts, sulfur, air and ethereal

* Euler's paper, as are so many of his publications, apparently is available only in its original Latin. Except for a discussion of Euler's concept of fire by academician Abbé Nollet in his physics textbook,[14] no significant statement on the paper appears to be available. The brief description here is based on Nollet's text.

matter and by a tiny, invisible vortex motion. (The latter idea is related to the Cartesian concept of vortex motion in the universe.[18]) Ensembles of particles in flames are swirling in tiny vortices and the individual particles themselves are in rapid spin. As the particles leave the flame, their spin velocity is increased and their vortex motion disappears.

The ignition of wood, for example, occurs when tiny vortices in a flame attack a region on the wood surface causing local particle agitation and enlargement of the pores. The vortex motion then spreads into the pores. Particles from the wood are released (combustion) and put into vortex motion (flame). The details of the mechanism are vague. The ethereal fluid plays a key role in causing the air to swirl in tiny vortices, which, in turn, activate the sulfur and salt. Combustibility variations among substances arise from differences in the concentrations of the water present and of the four essential ingredients.

Créqui in his "Explication"[11] based his concept of fire on notions of magnetism. He described a subtile substance that penetrates everything, flowing between the atoms of matter. This fluid has the unique property of rectilinear double-flow, permitting it to pass through a piece of wood, for example, along a straight path but simultaneously in opposite directions. The fact that the like poles of two bar magnets repel is cited as evidence that the subtile substance is flowing steadily from each end and, hence, in opposite directions simultaneously in the bar. Iron is unique, however, in that it does not permit full penetration of the subtile substance. Thus it has the tendency to move in a magnetic field.

The double-flow exerts two effects on bodies. Its pressure effect acts in holding matter together. Thus two atoms each having a contiguous flat side are pushed together securely. The rectilinear motion of the double-flow, however, acts to tear matter apart. Thus an atom only in insecure contact with another can be torn loose and caused to spin by the opposing flows. Differences in the state and the behavior of materials are traced to the prominence of one effect or the other and, hence, to the surface properties of the atoms. Combustion occurs when certain obstructions yield to the motion of the fluid. Atoms are broken away and put into spin. Since spinning atoms cannot remain close neighbors, they fly off into the air. The fluid apparently suffers some additional resistance in the air, because the flame signifies a continued breaking of obstructions.

Voltaire's Paper

Voltaire's paper "Essai sur la nature de feu et sur sa propagation"[11] is striking because he reported a variety of experiments that he had performed. This activity took place in a foundry near Cirey and in his rather spacious laboratory in the château, which had been constructed for his studies in physics. The story of science at Cirey has been told in a popular essay by E. M. Forster[19] and in well documented accounts by Libby,[3] McKie[20] and Walters.[6]

Voltaire's notions of fire correspond closely to those expressed by H. Boerhaave in his textbook "Elementa Chemiae," Leyden (1732).[3,18] Not departing from Aristotle, Voltaire considered fire to be an element as air, water, and earth. Light is fire, a conclusion based on burning glass demonstrations. Fire, he believed, is the source of motion, elasticity, and possibly electricity. The element, fire, is a fluid consisting of tiny hard spheres spaced sufficiently apart to permit crossing, such as the crossing of light beams. Fire is present in motion in the pores of matter;

a higher temperature corresponds to greater motion of the fire. He departed from Boerhaave by insisting that two different materials at the same temperature can have different fire concentrations. In spite of the popularity of the phlogiston theory in Germany, Boerhaave does not mention it[18] and, perhaps significantly, Voltaire does not either.

Bent on applying the Newtonian concept of attraction in explanations of phenomena in optics, Voltaire wanted to know for certain that fire has mass. Boerhaave, he noted, had come to the conclusion that it does not; he had found that a piece of iron (8 lb) did not increase in weight when it was heated to redness. But Voltaire pointed to work on the calcination of lead and powdered antimony where an increase in weight of the order of 10% had been measured. Obviously perplexed by the apparently conflicting results, Voltaire repeated Boerhaave's experiment in the foundry near Cirey. He weighed cold and hot iron in amounts up to one ton but found no change in weight. (At this time, June 1738, he wrote a series of very amusing letters in which he coached Abbé Moussinot on a mission to obtain opinions on calcination and on whether fire has weight from chemists Geoffroy and Grosse without revealing his, i.e., Voltaire's identity.[10])

Attempting to explain his results, Voltaire speculated that the gain in weight contributed by the addition of fire could be offset by the loss resulting from its thermal expansion. He considered then that the appreciable increase in weight noted for antimony calcined at the focus of a solar furnace might be due to a higher temperature of operation.

Therefore, in his next experiments, he worked with molten white iron, weighing amounts of 25, 35, and 100 lbs. and again after cooling six hours. These experiments, evidently repeated several times, showed an increase of about 4%. On the other hand, a similar series of tests with grey iron produced no increase in weight. No comments were made about the precision of measurements.

On considering both that the specific weight of iron decreases on fusion (an observation reported by Réaumur 11 years earlier) and that the concentration of fire in the hotter material should be greater, Voltaire entertained the idea that fire has no weight and that the increases noted in calcination are due to the addition of something from the atmosphere. [The latter idea had already been expressed by Du Clos (1667), Homberg (1705) and Hartsoeker (1706)[20].] But returning to the calcination results, he considered that, while the 10% was certainly not due to fire alone, it was probable that the weight of fire could not be excluded. To this he added that there is no reason why fire, an element, should not have weight. He quickly ended the discussion concluding that it is very probable that it does!

Voltaire's paper continues with a discussion of the propagation of fire. The motion of fire in the pores of liquids and solids may be increased by the addition of more fire or by shock or friction. When this motion is raised to a sufficient level, the momentum of the fire particles causes the progressive break down of the structure of solid and liquid; hence fusion, evaporation, decomposition, or combustion ensues. Attempting to formulate laws for fire behavior, he arrived at the following:

1. For a given heat source and time duration, the temperature rise in a body is related to its weight. On the basis of tests with iron strips of different size, exposed to a given wick flame, he reported that the temperature rise squared is inversely proportional to the square root of the weight.

2. The heating effect on a body varies inversely with the square of its distance from the source.

3. Fire introduced into bodies causes them to expand and to increase in weight before disintegration of their structure begins..

4. Bodies that need a longer time to heat, also require a longer time to cool. Significantly, he noted chalk as an exception, a supposed effect of a change in pore structure.

5. The rate of temperature rise of a body being heated increases to a maximum and then drops to zero as the final temperature is reached. His data are presented.

6. The rate at which fire enters a body is not proportional to the number of heating flames applied. Two wick flames required more than one-half the time taken by one to achieve a given temperature rise.

7. The rate of temperature rise, given a heat source, is greater for substances, e.g., sulfur, richer in fire content. His observations on the heating of wood and marble are reported.

8. Black bodies heat and cool more quickly than white. The rates for the colors are intermediate, decreasing from violet to red.

9. Owing to the inhomogeneity of materials, there may be departures from the foregoing laws.

Voltaire reported other observations on the transfer of the element fire from one body to another. He believed that fire moves along irregular paths in all directions. He showed that it passes equally up as well as down by sandwiching a flat piece of hot iron between two identical cold pieces and measuring their temperature 15 minutes later. To gain some idea about the proportion of fire passing from one body to another, he mixed boiling oil with an equal quantity of water at room temperature and measured a final temperature of 43° (Réaumur scale). With hot oil and cold vinegar he found 51°, and with hot oil and cold oil, 79°. The concept of specific heat had not yet appeared.

Voltaire was curious about the role of air in combustion. He burned off a patch, 20 ft×80 ft, prepared with brush and freshly cut sapplings on a calm and on a breezy (25 ft/sec wind) day and noted the difference in the rate. At the foundry, he heated at redness a closed sheet iron box containing 4 lbs of coal for 1½ hours. The coals lost 4 oz in weight, but they did not ignite until the box was reopened. Clearly air was necessary for complete combustion. But at higher temperatures, such as in a solar furnace, materials are broken down in the absence of air (in an evacuated chamber). He concluded that ordinary combustion requires air but high temperature combustion does not. In the extinguishment of (ordinary) fires, he stated, water cuts off the air supply and drains fire from the body.

Mme. Du Châtelet's Paper

Mme. Du Châtelet's paper "Dissertation sur la nature et la propagation du feu"[11] covers much the same material as Voltaire's but with additional excursions into the subjects of water freezing, the sun, and vulcanos. She shared the views of Boerhaave that fire does not have weight and that the concentration of fire in all materials at equilibrium is the same. Furthermore, unlike Boerhaave and Voltaire, she could not accept the unqualified impenetrability of fire. Her discussions are less anti-Cartesian than Voltaire's and are much more thorough and convincing.

Very pleased and even persuaded by her arguments, Voltaire publicly lauded her paper in June 1739.[9]

After having completed her paper on fire, Mme. Du Châtelet soon came under the influence of the Leibniz following in Germany. She rewrote her paper accordingly, replacing Newtonian- by Leibnizian-flavored statements and published it as a book in 1744. She had already published her Leibnizian book "Institutions de physique" (1740). Later she returned to the Newtonian camp at least to translate the "Principia" into French: "Principes mathématiques de la philosophie naturelle," published posthumously in 1759.

From his studies of fire, Voltaire stepped into the midst of a dispute among physicists that had been raging for a half-century, concerning the force of bodies in motion. The adventure proved to be more troublesome to him than satisfying. He withdrew from science in 1741, disenchanted and fearful that it might dominate his activities as a writer (Letter 2371, 22 August 1741).[21]

Conclusions

None of the five papers on fire represents a noteworthy contribution to science in the eighteenth century. Indeed scant attention was paid to them in the years that immediately followed. They do give, however, an intimate picture of diverse forces at play at this important period when the Aristotelian concept of fire as an element was being questioned and valid notions of oxidation and heat were starting to germinate.

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    No. 4. Leonhard Euler, "Dissertatio de igne, in qua ejus natura et proprietates explicantur," p. 5.

No. 10. le Père Lozeran de Fiesc, "Discours sur la propagation du feu," p. 25.
No. 11. le Marquis de Créqui, "Explication de la nature de feu et de sa propagation," p. 59.
No. 6. Anon., "Dissertation sur la nature et la propagation du feu," p. 87.
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ABSTRACTS AND REVIEWS

A. Prevention of Fires and Fire Safety Measures

Ames, S. A., Davies, J. P., and Rogowski, Z. W. (Joint Fire Research Organization, Borehamwood, England) "Performance of Metallic Foam as a Flame Arrester," *Joint Fire Research Organization Fire Research Note 809* (July 1970)

Sections: A, N
Subjects: Flame arresters; Foams, metallic

Authors' Summary

New metallic material resembling a structure of a sponge was investigated for application as a flame arrester. Its performance as a flame arrester in a tube was promising. Various grades were tested up to flame speeds of 200 m/s (600 ft/s) and with materials having similar resistance to air flow as commercial flame arresters no transmission of flame occurred.

Baldwin, R., Law, Margaret, Allen, G., and Griffiths, Lynda (Joint Fire Research Organization, Borehamwood, England) "Survey of Fire-Loads in Modern Office Buildings—Some Preliminary Results," *Joint Fire Research Organization Fire Research Note 808* (March 1970)

Section: A
Subjects: Fire-load; Offices; Statistics

Authors' Summary

Some results of a survey of the fire-loads and layout of two modern office buildings are given. It is shown that for these buildings the average fire-load per unit floor area (fire-load density) is 20 kg/m^2 (4.1 lb/ft^2), and is independent of the size of the room, and that in 95 percent of the rooms the fire-load density is less than 59 kg/m^2 (12 lb/ft^2); these buildings would thus be regarded as having a low fire-load. The mean fire-load per unit window area is 55 kg/m^2 (11 lb/ft^2), and in 95 percent of the rooms it is less than 147 kg/m^2 (30 lb/ft^2). On average the rooms are similar to those studied in recent experiments which indicate that fires in these rooms would be fire-load controlled.

Daxon, W. N. (Joint Fire Research Organization, Borehamwood, England) "Fire Risk in Dwellings in Multiple Occupation," *Joint Fire Research Organization Fire Research Note 817* (April 1970)

Section: A
Subjects: Dwelling; Fire risk; Occupation, multiple

Author's Summary

The Ministry of Housing and Local Government have been studying general problems arising from the multi-occupation of dwellings, and with "fire risks" in mind a survey was carried out to try to obtain precise statistical information.

A detailed study, over a period of six months, of fire reports from five local authorities known to have in their areas a high proportion of multiple occupancy dwellings, suggests that the risk of fire is five times as great in these dwellings as in single occupancies, and the probability of becoming a fire casualty is twice as great; that of being trapped, having to be rescued, or being forced to escape, is almost seven times as great.

Oil heating appliances are the main single cause of fires in multiple occupancies.

Heselden, A. J. M. and Theobald, C. R. (Joint Fire Research Organization, Borehamwood, England) "The Prevention of Fire Spread in Buildings by Roof Vents and Water Curtains. Part 2. The Effect of Air Movement on Water Curtains," *Joint Fire Research Organization Fire Research Note 812* (April 1970)

Section: A
Subjects: Building; Drops; Fire spread; Vents; Water curtains

Authors' Summary

The earlier part of this report* showed how roof venting—if extensive enough—could remove all the combustion products of a fire. If this was not enough to prevent spread altogether, wetting down of fuels heated by radiation could prevent their ignition. However, venting induces draughts towards the fire and if these are strong, weak water sprays can be deflected into the fire, where they would be less effective.

An attempt to use the minimum effective water quantities for wetting down may thus be ineffective.

This report describes experiments on the deflection of water curtains by an air stream and shows how the effect can be calculated with the necessary degree of accuracy so that the data reported can be provisionally extrapolated to situations other than those examined experimentally.

With draughts of up to 1.2 m/s, a water flow of 0.5 $m^{-1} s^{-1}$ can give sufficient width of wetted fuel 5 m below the nozzles to prevent fire spread.

* *Fire Research Abstracts and Reviews 12*(2), 128 (1970).

Lawson, D. I. (Joint Fire Research Organization, Borehamwood, England) "A Laser Beam Fire Detection System," *Joint Fire Research Organization Fire Research Note 824* (April 1970)

Section: A
Subjects: Detectors; Fire detectors; Laser

Author's Summary

Details of a fire detection system using the deflection of a laser beam above a fire are described. It is shown that such a system will decrease in sensitivity with the height of the compartment to be protected at a lower rate than with point detection systems. Devices are described for preventing false alarms due either to building disturbances or to ambient variations in temperature.

It is claimed that such a system would have economic advantages over other systems and that it could readily be adapted to give intruder protection.

Morris, W. A., Hopkinson, J., and Malhotra, H. L. (Joint Fire Research Organization, Borehamwood, England) "Fire Hazard of Expanded Polystyrene Linings," *Joint Fire Research Organization Fire Research Note 827* (May 1970)

Section: A
Subjects: Ceilings; Domestic; Fire hazard; Lining materials; Polystyrene

Authors' Summary

The use of expanded polystyrene wall linings and ceiling tiles has increased in recent years and reports have been made on fires in domestic buildings where the material had been used. The present investigation was undertaken to determine the fire behaviour of linings of expanded polystyrene in the thicknesses used in domestic buildings. The experimental work utilized ad hoc test procedures ranging in scale from 900 mm^3 boxes to full-size rooms and covered such factors as the method of fixing, type of material, and decorative finishes.

For the range of situations covered by this investigation the tests have established that the behaviour of the material fixed in place by an adhesive is different from that shown by an examination of small samples. It has been concluded that when applied to a suitable substrate with an overall application of adhesive and left undecorated the linings do not present a fire hazard. The use of flame retardant paints is to be recommended for safety but with a matt-finish emulsion paint the finished linings provide an acceptable level of safety for domestic buildings. The use of gloss finishes on this material represents a serious fire hazard and should be avoided.

Palmer, K. N. "Flame Arresters for Pressure Relief," *Electrical Times,* Focus 15–18 (June 26, 1969)

Section: A
Subjects: Arresters, flames; Flame arresters; Pressure relief

Abstract by Safety in Mines Research Establishment, England
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New methods of protection are needed for certain situations, e.g., where equipment is mobile and therefore needs to be of minimum weight, but also involves substantial currents, also to provide equivalent safety but at lower cost than traditional methods. One such new technique currently being developed at the Fire Research Station, Borehamwood, involves the use of flame arresters to protect equipment, particularly that which sparks in normal use. The principle is that should ignition occur within the equipment the pressure is released by means of vents in the casing and the emission of flame through the vents is prevented by flame arresters. The design data already available at the Fire Research Station is sufficient for a first prototype to be constructed. After testing, modifications may be needed and the construction of the casing then needs to be assessed in detail to ensure that flame cannot escape around the lid or at shaft or cable entries. The method of test of the effectiveness of flame arresters is described and the future prospects of the technique.

Riddlestone, H. G. "Electrical Equipment for Hazardous Atmospheres," *Electl. Rev.* **185**(6), 205–206 (August 8, 1969)

Section: A
Subjects: Atmospheres; Electrical equipment; Hazardous atmospheres; Hazards

Abstract by Safety in Mines Research Establishment, England
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The author reviews recent national and international efforts aimed at standardization of equipment and system design and construction.

Wilde, D. G. and Roberts, A. F. "Fire-Retardant Coatings for Mine Timber: The Effect of Coating Thickness," *The Mining Engineer* **128,** 123–130 (1968)

Section: A
Subject: Retardants

Abstract by Safety in Mines Research Establishment, England
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The fire risk in timbered mine roadways can be reduced by giving the timber a fire-retardant treatment. Impregnation of the timber by suitable salts provides the best means of treatment but surface coatings are the only form of treatment that can be applied to standing timber. The main variable affecting performance of a coating, within the control of the user, is its thickness. This paper suggests a minimum thickness of coating of a sodium silicate/limestone compound and of a coating of "Hardstop" necessary to achieve in practice an acceptable degree of protection. The performance of coatings was assessed by using the Preliminary Surface Spread of Flame Test (BS 476: Part 1); coatings were considered to be satisfactory if they raised the underlying timber to Class 1 level in the test. It is recommended that, in mines, coatings of sodium silicate/limestone compound should be 1–02 mm (0.040 in.) thick if applied to hardwood and should be 3–2 mm (0.125 in.) thick if applied to softwood. It is very important that coatings should be continuous on all surfaces available for treatment and that they should adhere well to underlying timber. "Hardstop" coatings do not adhere well to dry wood. Sodium silicate/limestone coatings are more effective for a given thickness than "Hardstop" coatings and study of the porosities of the materials suggests that, in part, this may be because the silicate compound is a more effective sealant, particularly when heated, than is "Hardstop." The silicate compound only is recommended for use in mines.

Young, R. A. (Joint Fire Research Organization, Borehamwood, England) "Fire Tests with Sprinklers on High Piled Stock," *Joint Fire Research Organization Fire Research Note 814* (March 1970)

Sections: A, G
Subjects: Detector, fire; Extinguishing; Fire spread; High-piled; Sprinkler; Storage

Author's Summary

A recent development in the industrial field is the introduction of high-stacked storages of heights ranging from 6 m (20 ft) up to as much as 30 m (100 ft) or more. These storages create a high fire hazard both in their configuration and in the immense value of the goods in them. The detection and extinction of fires in them is of paramount importance.

This note describes an investigation of the efficacy of a conventional sprinkler system, combined with the latest means of fire detection in controlling fires developing in a palletised storage of height 7.3 m (24 ft), consisting of two rows of back-to-back pallets at four levels.

The main avenues of fire spread were found to be up the vertical gaps between the goods, rather than up the outer face of the stack, and it was found that sprinklers installed on the longitudinal axis of the rack to cover each gap at alternate levels controlled the fires, without the fires ever reaching serious proportions.

It was also found that the detection systems gave a warning of fire from 3 to 7 min before the first sprinkler operated.

B. Ignition of Fires

Bowes, P. C. (Joint Fire Research Organization, Borehamwood, England) "Thermal Ignition in Two-Component Systems, Theoretical Model," *Combustion and Flame* **13**(5), 521–530 (1969)

Section: B
Subjects: Explosion, thermal; Ignition, explosion; Ignition, thermal; Two-component ignition

Reviewed by J. B. Howard

This paper presents a mathematical analysis of thermal ignition in two-component systems. The analysis, which is similar to the classical treatment of Semenov and Frank-Kamenetsky, derives critical conditions for ignition by studying the relationship between the temperature rise and the progress of oxidation. The self-heating system consists of two, independently reacting components, one inexhaustible component can cause a temperature rise in excess of the upper stationary, but unstable, value possible for the inexhaustible component reacting alone.

The basic model consists of an energy balance which gives a differential equation relating the rates of conduction, heat generation, and temperature rise. The specimen can be either a plane slab, an infinite cylinder, or a sphere by proper choice of a geometric constant. The heat-generation term is the sum of the contributions of the two, uniformly mixed components. In two different parts of the analysis, reaction of the exhaustible component is assumed to be first-order and autocatalytic, respectively. In both cases reaction of the inexhaustible component is assumed to be zero-order and both rate constants are given by Arrhenius equations with the Frank-Kamenetsky exponential approximation replacing the Arrhenius terms.

The dimensionless quantities appearing in the equations have the form familiar in thermal explosion theory for one-component system, but the significance of some of the quantities is slightly modified. Two of the quantities, one for each component, are interpreted as the Frank-Kamenetsky self-heating parameters for the two-component system. In each quantity one component is the sole reactant and the other component is an inert diluent. Another important quantity is the dimensionless temperature rise for the system with the exhaustible component acting as sole reactant. Another parameter, a new quantity, is the ratio of rates of heat evolution by the two components at the ambient temperature.

Approximate numerical results illustrate the magnitude of the contribution of the different parameters to criticality for some conditions of practical importance. It is suggested that, with criticality dependent on three or four disposable parameters, more exact machine calculation would be of no increased general interest but would be valuable for specific applications.

Some general consequences of the exhaustible component on the relation between specimen size and critical temperature for ignition of the two-component system are outlined as follows. In the usual way, as size is increased the critical ambient temperature for ignition is reduced. In one region of parameter values the contribution of the exhaustible component becomes increasingly important at the lower temperatures. Under such conditions the maximum effect that can be exercised by the exhaustible component is determined by the temperature rise it can produce in the system under adiabatic conditions.

In another region of behavior, the influence of the exhaustible component decreases with increase in specimen size and reduction of critical temperature. Although, in principle, examples of this case could occur in practice and affect predictions from small-scale ignition tests at high temperature, experience suggests such behavior is rare compared with that described above.

The paper gives some comparisons of the theoretical results with literature data. Further testing of model with experimental observations is said to be forthcoming.

Fry, J. F. and Eveleigh, Christine (Joint Fire Research Organization, Borehamwood, England) "The Behaviour of Automatic Fire Detection Systems," *Joint Fire Research Organization Fire Research Note 810* (March 1970)

Sections: B, L
Subjects: Alarm; Alarm, false; Automatic; Detector fire

Authors' Summary

An examination has been made of the frequency and reasons for the occurrence of false calls made by automatic fire detection systems. These appear to be about 11 times as frequent as calls to genuine fires. About one-quarter of false calls are attributed to ambient conditions, one-half to mechanical and electrical problems, and about 17 percent to failure in or misuse of the communications systems. Where automatic systems are installed about 68 percent of calls to genuine fires are made by them.

Gray, P. (Defence Standards Laboratories, Melbourne, Australia*), **Lee, P. R. and MacDonald, J. A.** (University of Leeds, England†) "Thermal Explosion in the Sphere and the Hollow Spherical Shell Heated at the Inner Face," *Combustion and Flame* **13** (5), 461–471 (1969)

Sections: B, G
Subjects: Explosion, thermal; Ignition; Thermal explosion

Authors' Abstract

The steady-state heat conduction equation for reactants of spherical symmetry decomposing by a zero-order exothermic process has been converted by means of the fifth-power (quintic) approximation

$$\exp(-E/RT) \doteq \exp(-E/RT_0)(\alpha+\beta\theta)^5$$

(where α and β are constants) into a form which is soluble analytically. The method of solution depends upon the physical model under examination: two models have been discussed, that of self-ignition of a hollow spherical shell of reactant heated at the inner face and cooling to the surroundings from the outer face and the solid sphere immersed in a constant temperature bath.

Approximate Frank-Kamenetskii criticality criteria for hollow spheres of varying thickness and hot face temperatures were derived analytically by a method involving the use of incomplete elliptic integrals of the first kind. The results were compared with numerical solutions of the equation wherein the exponential approximation had been made and found to be in good agreement. It has been shown how these results fit into the pattern established by those for the asymmetrically heated slab and the infinite hollow cylindrical shell heated at the inner face.

For the first time an analytical criticality criterion ($\delta_{\text{crit.}}=\frac{3}{4}\alpha^4\beta$), critical centre temperature rise $[\theta_{m,\text{crit}}=(\sqrt{2}-1)(\alpha/\beta)]$ and temperature distribution, given by

$$(\alpha+\beta\theta)^2=\frac{1.5\alpha^2[(1+z^2)-(1-z^2)\{1-(4\alpha^4\delta\beta/3)\}^{1/2}]}{[\delta\beta(1-z^2)^2\alpha^4+3z^2]}$$

have been determined for the sphere by a method in which the phenomenon of criticality emerges naturally from the analysis.

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C. Detection of Fires

European Fire Alarm Manufacturers Association (EURALARM), March 12, 1970, Headquarters of the Association of the Swiss Machinery Manufacturers, Zurich, Switzerland

Section: C
Subjects: Alarms; Fire alarm; Manufacturers Association

Press Release

EURALARM, the Association of European Fire Alarm Systems Manufacturers, with British participation, was formed at a special inaugural meeting in Zurich. The meeting was attended by 24 delegates from 12 countries. Directly or indirectly, they represented 37 European companies.

History

The growing acceptance of early warning systems has increased the interest shown in them not only by the fire protection industry itself but also by government departments and sponsored bodies, universities, testing institutes and insurance companies. Naturally each is concerned with different aspects of the subject ranging from the sociological, economic and commercial potentialities to the technical standards.

There has been a general trend towards professional and trade associations uniting to form European parent associations. In the area of fire protection this has been exemplified by the C.E.A., the European Committee of insurers, and the organisation responsible for standards.

In 1966 the C.E.A. formally reported its aims for the unification of automatic fire detection rules at an Aachen seminar organised by the Institute of Electrical Telecommunication Technology, which acts as C.E.A.'s technical secretariat. After representatives from all parts of the world had further discussed the 1966 proposals, it became clear that a prerequisite for the establishment of sound standards for the industry was a European committee. Such a Committee was formed in the Aachen seminar of January 1969 by 20 representatives from six countries. It was the work of this committee that resulted in the inauguration of EURALARM.

Membership

Membership of EURALARM is limited to national associations of fire alarm systems manufacturers. At present, however, such associations exist in only a few countries. Individual companies may, therefore, become members of EURALARM, providing that their membership expires as soon as a national association is founded. The following national associations opted for entry into EURALARM at the inaugural meeting:

BEPSA, the British Fire Protection Systems Association, London
ZVEI, the Federation of the German Electrotechnical Industry, which incorporated a branch dealing with Detecting Systems for the Protection of Life and Property

The founding of further national associations is expected.

At present, individual companies from the following countries are members: Belgium, Denmark, France, Yugoslavia, Portugal, Netherlands, Sweden, Switzerland.

Elections

The following officers were elected at the inaugural meeting.

Chairman	Herr H. Krenzlin (Germany)
Vice-Chairman	Mr. A. Jörgensen (Sweden)
Auditors	Dr. H. Marti (Switzerland)
	Mr. A. Wedholm (Sweden)

General Purposes Committee

A committee was set up to discuss urgent problems, including the Test Scheme for Automatic Fire Detectors, proposed by the Aachen Institute. Officers and Constitution:

Chairman	Mr. Thomas Lampart (Switzerland)
Vice-Chairman	Mr. B. Teglöf (Sweden)

One delegate each from Belgium, Germany, France, Great Britain, Yugoslavia, Netherlands, Norway, Sweden, Switzerland, and Spain.

Relation with Other Organisations

EURALARM realizes that good relations with other European organisations will be of great importance, particularly with EUROFEU, the European Committee of the Manufacturers of Fire Engines and Apparatus. There will be mutual ground for discussion with EUROFEU, especially with its committee on Smoke and Fire Detection.

Invitation to cooperate: All manufacturers of equipment and systems for automatic fire detection as well as all national associations of such manufacturers are invited to join EURALARM, declares the Chairman. "Unity in the fire alarm industry is vital. We will be delighted to send further information to anyone interested." Enquiries should be addressed to:

EURALARM,
Fachabtelung Meldeeinrichtungen zum Schutze von,
Leben und Sachwerten,
Zentralverband der Elektrotachnischen Industrie e.V.,
Kriegerstrasse 17,
D-7000 Stuttgart, Germany

D. Propagation of Fires

Matula, R. A., Orloff, D. I., and **Agnew, J. T.** (Drexel University, Philadelphia, Pennsylvania) "Burning Velocities of Fluorocarbon-Oxygen Mixtures," *Combustion and Flame* **14**(1), 97–101 (1970)

Sections: D, G
Subjects: Burning velocities; Fluorocarbon-oxygen

Authors' Abstract

The burning velocities of mixtures of perfluoropropene (C_3F_6), perfluorocyclobutene (c-C_4F_6), and perfluorocyclobutane (c-C_4F_8) with oxygen at atmospheric pressure are reported. The peak burning velocity of fluorocarbon-oxygen mixtures cannot be correlated with the peak calculated adiabatic flame temperature, but it is shown that the peak burning velocity can be correlated with maximum equilibrium fluorine atom concentration. These results indicate that the flame propagation mechanism in fluorocarbon-oxygen systems is dominated by diffusion of reactive fluorine atoms from the hot products into the unburned reactants rather than by thermal effects.

Thomas, P. H. (Joint Fire Research Organization, Borehamwood, England) "The Rates of Spread of Head Fires in Gorse and Heather," *Joint Fire Research Organization Fire Research Note 796* (January 1970)

Section: D
Subjects: Fire spread, rate; Fire spread, wildland; Fire spread, wind

Author's Summary

Various measurements made during ten controlled head fires in the New Forest have been reported by Woolliscroft, who calculated that flame radiation contributed significantly to the spread. Here, these data are discussed further.

There are two or three apparently anomalous rates of spread which one cannot resolve with the few data available, but the rate of spread is broadly related to the amount of fuel and the wind speed,

$$\text{viz} \quad R\rho_b = a + bU$$

where R is the rate of spread in m/s
ρ_b is the bulk density of the fuel in kg/m^3 (including water content)
U is the wind speed m/s
a is 0.15 kg/m^2 s^1
b is 0.16 kg/m^3

An estimate has been made of the attenuation coefficient k' in a relation between the emissivity of the flames ϵ_f in head fires and D the length of the flame zone,

$$\text{viz} \quad \epsilon_f = 1 - \exp(-k'D)$$

These data give $k' = 0.10\ m^{-1} \pm 0.036\ m^{-1}$ which is lower than the figure employed by Woolliscroft and leads to lower estimates of flame radiation. Although it would seem possible to attribute the effect of wind solely to its effect on flame radiation, considerations of stability suggest that even these lower estimates of flame radiation are too high (perhaps because the flame is more like a series of separate flames than a continuous one) and convection must play a role at least comparable to flame radiation.

An equation for 'R' which is practically as accurate as the above and has some theoretical justification but is more complicated has been obtained by assuming heating by convection is proportional to wind speed.

Vodvarka, F. J. (IIT Research Institute, Chicago, Illinois) "Urban Burns—Full-Scale Field Studies," *Final Technical Report under Office of Civil Defense Contract DAHC-20-70-C-0213 Work Unit 2562A* (January 1970)

Section: D
Subjects: Fire damage; Fire growth; Fire spread; Firebrands; Full-scale experimentation

Author's Summary

Extensive detailed computer models of mass fire spread suffer from lack of adequate input. Some input parameters do not lend themselves to deductional processes nor to laboratory scaling. However, buildings in the path of urban redevelopment or highway construction sometimes become available for fire experiments at reasonable costs. The objective of this project was to utilize some of these structures to obtain an optimum of fire behavior and spread data by designing the experiment to the structure.

Five two-story frame residences, one two-story cement block residence, a brick tavern, and a cement block automotive filling station were utilized in the experiments. Data on fire spread rate radiant heat fluxes, firebrand fallout, buoyancy pressures, and gas composition were among the data obtained.

Burn 69–1 was an old two and one-half story frame farmhouse in very poor condition. The burn was designed to obtain data on internal fire spread and to develop a refinement of firebrand spotting techniques. Instrumentation for temperatures, radiant, convective and total heat fluxes and wind conditions was set up. Plastic sheets of four types were laid leeward of the structure at distances to 600 ft.

The venting of the roof and holes in the floors caused the fire to spread rapidly from the original upwind ignition point. The fire doubled in volume every $5\frac{1}{4}$ minutes after the initial flashover. At the peak of the fire flames reached an estimated 60 ft above the mansard roof. Radiation levels at the threshold of spontaneous ignition were attained in the leeward direction when the roof caved in and the front of the structure burned away to reveal much of the flaming interior.

Firebrand fallout was quite general within 150 to 200 ft in the leeward quadrant from the building, but was highly directional beyond that distance. Most brands beyond 200 ft were within a 15 degree angle which passed between two spokes along which the sheets were laid. Extinguished firebrands were observed up to 2000 ft from the fire. Firebrand densities were 50 per 100 sq ft although in one localized area a density of 500 per 100 sq ft was found.

Burn 69–2 was a flashover experiment in a large space. The space was a $33\times36\times10$ ft public room in a heavily constructed one-story brick tavern with living quarters at the rear. Fuel load consisted of combustible furniture in the living quarters and primarily wood pallet simulations of tables in the public room.

Under light and variable wind conditions and with all but three openings closed, the fire required more than one hour to flash the large room. Flashover occurred simultaneously through the entire volume. The fire was oxygen starved for another 10 minutes before it broke through the roof and proceeded to spread at a rate of doubling its volume every 41 minutes. The low rate of spread was due to the large initial volume and to the brick firewalls separating the public room from the living quarters. The air indraft at the back door when the fire broke through the roof was estimated at 20 to 25 mph.

The heavily asphalted built-up roof burned with an extremely heavy black smoke cloud which also shielded the flames from the calorimeters. Peak CO and CO_2 concentrations were 1.36 and 3.7 percent, respectively. The oxygen concentration minimum was slightly below 17 percent. Gas pressures measured under the roof were 0.14 in. H_2O just before roof "burnthrough."

Burn 69–3 was a crib experiment in an automotive service station built of cement block. Two experiments were made; one on the sales area, the other in the service bays. Wood pallets were stacked to provide fuel for the burns, intended to verify radiation intensities from fuel surface controlled fires. The results were mixed. Measurements from the first fire were in good agreement with predictions, while those from the second fire were too low. Bowing roof panels and cracked cement blocks indicated the structure to be unsafe for further experiments or for habitation.

Burn 69–4 was in a well-preserved old two and one-half story residence covering 2200 sq ft of living area. The experiment was designed to establish the downward spread of a well-developed fire under minimum ventilation conditions.

Starting in a second-floor upwind room, the fire flashed over in $18\frac{1}{2}$ min, then doubled in volume on the floor of origin each $4\frac{1}{2}$ minutes, and required 12 minutes to spread downward by way of the stairwell. Upper treads apparently ignited from radiation; lower stairs by pilot ignition. First-floor spread closely approximated that of the second. The wood-shingle roof released large amounts of white smoke to shield the calorimeters effectively. Radiant measurements were quite low. Gas pressures under the mansard roof were greatest—0.16 in. H_2O at roof "burnthrough."

Burn 69–5 was in a two-story cement-asbestos sided country house which had been converted into two apartments. The experiment was to establish an upwind fire spread rate and to collect firebrands. The latter objective was voided by a wind switch after ignition.

After flashover of the ignition room on the downwind side of the house, the fire doubled in volume initially every 7 minutes—somewhat slower than the previous fires in frame structures. After the fire had opened up the roof and attic spaces, the spread rate was cut to almost one-third, spreading at a rate equivalent to a doubling every 18 minutes, the fire changed to an essentially surface-controlled mode. The calorimeters measured very moderate values of radiant heat flux, 0.23 cal/cm² sec being the greatest flux at right angles to the wind. Gas pressures under the roof were 0.19 in. H_2O—about two-thirds of the theoretical value. Although firebrands were observed landing on the wood-shingled roof of a barn 200 ft north no ignitions occurred. The brands were probably nearly expended upon landing but a light misty rain was a contributing factor.

Burn 69–6 was in a wood-shingle-roofed two-story farm house located next to an aerial telephone cable. Because of the need to protect the cable, the experiment was designed for fire spread from a roof ignition. Ignition was from four discrete burning drips of jet fuel on the kitchen roof. The fire spread and grew until the main roof ignited 17 minutes later. Burning from the top, the structure burned in essentially a fuel surface-controlled mode and flashover of the various spaces was difficult to assess. The volumetric spread rate could not be determined; however, it was slower than a ventilation-controlled fire. Fire duration was about $1\frac{2}{3}$ hours.

Although firebrand fallout measurements were not possible, firebrand activity was encountered. Few live brands were found from the wood shingles. Late in the fire when 10 to 15 mph winds occurred during structural collapse, at least 29 fires were started mostly on the roof of a shed 100 ft away. Very low radiant heat fluxes, on the order of 0.07 cal/cm² sec were measured by the leeward calorimeter.

Burn 69–7 was in a two-story dwelling which was clad in an asphalt- and gravel-covered insulating board. The burn was planned to determine the effects of strong gusty winds. The fire was started in a pile of loose paper upwind on the first floor. Under the influence of the gusty 10 to 20 mph winds the flames spread through the house so rapidly the initial volume doubling time is estimated to be less than one minute. Enormous flames and clouds of black smoke were emitted from the building as the wind-whipped fire attacked the asphalt outer covering. Sections of the insulating board measuring 1×3 ft$\times\frac{5}{8}$ in. were seen flying through the smoke. At least 8 spot fires were started. The first floor of the ignition wing collapsed, dropping the entire second floor and roof to the ground. A few minutes later the main structure roof buckled and the entire remains folded as a parallelogram into a pile of rubble. The entire fire lasted less than 25 minutes.

The wind-whipped flames drove some thermocouple outputs beyond the 2400 degree calibration of the recorder. However, the heavy smoke shielded the flames so that the maximum measured radiant flux was only 0.47 cal/cm²-sec. Firebrands missed the main array of plastic sheets but landed on a 400 ft long strip of sheets laid along a road oblique to the wind path. The average brand density was 118 per 100 sq ft, while the greatest was 233 per 100 sq ft. Most of the brands were quite small. Only 1 "C" size and 8 "C/2" size brands were found.

Burn 69–8 was in a two-story cement block residence which had interior walls finished in thin ($\frac{1}{4}-\frac{3}{8}$ in.) lime plaster. An open two-story front hall joined the two floors. The experiment was to investigate the capability of a drapery ignition to spread fire into the interior, to measure gas concentrations in a rubble fire and to collect firebrand data. The gas monitoring was unsuccessful when condensate caused the instruments to go out of calibration.

The trash fire ignited a curtain on the back porch which fell on piles of clothing on the floor. However, the flames decreased in intensity and would have required considerable time to communicate the fire to the base of a stairway. A second fire was started in a closet on the first floor. The fire spread moderately, with a volume doubling time of 9½ minutes. After 29 minutes the first floor walls collapsed, dropping the second floor. Five minutes later the roof collapsed filling the block walls outward and leaving a burning pile of rubble.

The ignition mechanism of the drape was by impingement of the flames against it. The maximum radiant flux measured during the fire was 0.25 cal/cm^2-sec. Gas concentrations reached the maximum calibration values within 15 minutes after the second ignition and were greater than 2 and 5 percent for CO and CO_2, respectively, when the system failed. Oxygen content at shutdown was 8½ percent. Gas pressures under the roof were very erratic and peaked at 0.16 in. H_2O at roof breakthrough. Firebrand fallout was measured over a 25 degree sector with practically all the brands falling within 320 ft and about 80 percent within 200 ft. Most of the brands were quite small.

An integral part of the contract called for the revision of the gas sampling and analyzing system and the upgrading of the appurtenances in the trailer. To this end, the gas system was repiped, using three-way valves and control valve equipped flowmeters. The pumping system was simplified, using only one of the motor-pump sets and mounting it on the trailer tongue. A cam timer was substituted for the electronic one.

A 30-channel instrumentation patch board was built and installed. A 180-ft three-wire input power cable was purchased. Two field power cables were also obtained. Three 100-ft and one 200-ft 22 conductor instrument signal cables and a 250-ft 9 conductor signal cable were provided. All cables are on cord caddies and include terminal equipment.

Three calorimeters were provided as part of the instrumentation package. Also included were a hygrometer and a demountable anemometer. Permanent mounts for four OCD-owned L&N recorders and four IITRI recording instruments were provided.

Rainaldi, Nicola (Montecatini Edison, S.p.A, Italy) "Advance Report on Halon 2402," *Fire Technology* 6(1), 59–67 (1970)

Section: D
Subjects: Freons; Halon 2402

Reviewed by J. B. Levy

Halogenated hydrocarbons represent a well-established class of flame-inhibiting agents and in the present report the characteristics of Halon 2402 (dibromotetrafluoroethane) pertinent to its application as a fire extinguisher are discussed. These characteristics include the toxicity of the agent itself, of the pyrolysis product produced in its use, the dielectric properties of the material, its effectiveness as a fire-extinguishing agent and the parameters important in its application to actual fires.

Toxicity studies of the agent itself were carried out by subjecting rats to atmospheres containing various concentrations of the agent and by injection into the peritoneum. The conclusion was that, by a classification system of the U.S. National Academy of Sciences, Halon 2402 would be rated as a relatively harmless substance. Although the decomposition products that could result in a fire situation, e.g., hydrogen fluoride, hydrogen chloride, carbonyl fluoride, are considerably more toxic than the agent itself, tests in which *n*-hexane fires were extinguished by Halon 2402 showed that the product concentrations resulting were well below any lethal concentrations. In comparison with carbon dioxide, Halon 2402 was considerably better both as an extinguishing agent and in terms of the toxicity of the resultant atmosphere. Tests showed that the absolute dielectric strength of Halon 2402 is such as to pose no hazard in its use in electrical fires. Thermal decomposition tests under fire conditions showed that so little decomposition occurred that the main toxicity considerations are those of the agent rather than the products.

The method of application of any agent is clearly important. Here the parameters of the droplet sizes, the nozzle geometry, the nature of the pressurizing gas and the operational pressure were considered and optimal conditions established both for indoor and outdoor fires.

The conclusions drawn were that Halon 2402 is an effective fire extinguishing agent and that the present state of knowledge permits its practical application now.

E. Suppression of Fires

Edmondson, H. and **Heap, M. P.** (University of Salford, Salford, England) "The Burning Velocity of Methane-Air Flames Inhibited by Methyl Bromide," *Combustion and Flame* **13** (5), 472–478 (1969)

Sections: E, D
Subjects: Burning velocity; Flames; Inhibition; Methane-air; Methyl bromides.

Reviewed by W. J. Miller

This paper comprises an extensive set of painstaking measurements of burning velocity in methane/air flames with and without methyl bromide added as inhibitor. The measurements were made on a nozzle burner designed by Scholte and Vaags[1] to produce uniform radial velocity profiles. With such a velocity profile the burning velocity, S_u is given by the expression

$$S_u = V_g \sin\theta$$

where V_g is the unburned gas velocity and θ is half the apex angle of the conical flame measured with a schlieren optical system.

It is in the measurements of unburned gas velocity that this paper makes its principal contribution. The authors note that the gas flow in the region immediately upstream of the flame front is perturbed by the combustion wave and the velocity in this region is therefore not equal to that issuing from the burner mouth. The magnitude of the perturbation is an undefined complex function of gas velocity and fuel/air mixture strength. Miniature Prandtl-type Pitot-static tubes were inserted through the flame front to obtain direct measurements of the local gas velocity in the preheating zone. Considerable deviations from the gas velocity, calculated simply from volume flow rate and burner cross section, were observed, which amounted (in the worst case) to as much as 8%. The burning velocities computed using the above relationship and measured gas velocities are satisfyingly independent of gas velocity (unlike some previous measurements[2]), and for methane/air mixtures are somewhat lower than those from previous studies[1,2] (36 cm sec^{-1} for the stoichiometric mixture compared to about 40 cm sec^{-1}).

The effects of methyl bromide are in qualitative accord with prior work: (1) the inhibitor is more effective in rich mixtures; (2) the maximum in the plot of burning velocity versus stoichiometry is shifted by the inhibitor toward leaner mixtures (due simply to the addition of fuel in the form of CH_3Br); (3) the inhibiting effect is proportional to inhibitor concentration. The highly precise nature of these measurements reveals that successive equal increments of inhibitor cause progressively smaller decrements in burning velocity; this effect is small and had gone unnoticed in previous work.

The mechanistic implications of these findings are discussed in terms of the inhibition mechanisms of Rosser, Wise and Miller,[3] and Wilson.[4] The authors conclude that the inhibitor decomposes to CH_3 and Br in the preignition zone. This conclusion, however, ignores the compelling arguments set forth by Wilson,[4] and Wilson, O'Donovan and Fristrom[5] that the processes responsible for the retardation of combustion by CH_3Br are due to the fact that the inhibitor does *not* decompose in the preignition region but on the contrary must be stable enough to retain its identity to a point where it may react preferentially with H and OH which would otherwise produce chain branching.

The care with which the gas velocity measurements in this study were made make these burning velocity determinations probably the most accurate work of this nature presently available. Unfortunately our quantitative understanding of the inhibition process is not yet sufficiently sophisticated to allow meaningful comparison of the data with theoretical predictions.

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5. Wilson, W., O'Donovan, J. T., and Fristrom, R. M.: *Twelfth Symposium (International) on Combustion* (Combustion Institute, Pittsburgh, 1969), p. 929.

Landesman, H. and **Basinski, L. E.** (National Engineering Science Corporation, Pasadena, California) "Investigation of Fire Extinguishing Agents for Supersonic Transport," *Final Report under Air Force Contract TDR-63-804 Aero Propulsion Laboratory, Wright-Patterson AFB* (September 1963)

Sections: E, H
Subjects: Chemistry; Combustion; Fire extinguishment; Inhibition; Supersonic transport

Authors' Summary

Properties of ten compounds which have passed screening for possible use in the in-flight fire extinguishing system of the supersonic transport are tabulated. Reported are boiling points, freezing points, densities, viscosity-temperature curves, critical temperatures and pressures, heats of vaporization, specific heats, pressures at 500°F and thermal stabilities under testing conditions. Also reported are the inhibitory effects of each compound on heptane-air flammabilities, estimated costs, and compatibilities with various metallic and non-metallic materials. Potential toxicities are discussed. ✓

Limited physical properties of an additional 24 materials which did not pass this preliminary screening are tabulated. Recommendations are given for more extensive work on acceptable compounds to further define their usefulness under SST flight conditions.

F. Fire Damage and Salvage

Baldwin, R. and **Allen, G.** (Joint Fire Research Organization, Borehamwood, England) "Some Statistics of Damage to Buildings in Fires," *Joint Fire Research Organization Fire Research Note 805* (March 1970)

Sections: F, L
Subjects: Building; Damage; Fire; Statistics

Authors' Summary

Statistics of damage to industrial and storage buildings in Hertfordshire are analysed. It is found that the probability of structural damage is about 14 percent, and the chance of failure of a structural element is about 0.5 percent. About half the fires have damage less than 10 m^2, about three-quarters less than 100 m^2. The extent of damage appears to be associated with the size of fire as represented by the probability of spread beyond the room of origin.

G. Combustion Engineering

Babkin, V. S. and **Kononenko, Iu. G.** (Novosibirsk) "Analysis of the Equations for Determination of the Normal Flame Velocity by the Constant-Volume Bomb Method," *Physics of Combustion and Explosion* **5,** 84–93 (1969). In Russian

Section: G
Subjects: Flame velocity; Constant-volume bomb

Authors' Summary—Translated by L. J. Holtschlag

The normal flame propagation velocities are calculated and compared individually on the basis of various forms of approximate equations, specifically, equations with density (pressure) and flame-radius derivatives, but with different relations for the weight fraction of the combustion products, so as to increase the theoretical accuracy of the flame velocity equation. The calculations presuppose the use of the constant-volume bomb method. Additional corrective expressions are derived to account for the variable experimental heat-capacity ratio. Initial, additional, and combined relations are applicable in general to the initial stage, the final stage, and to the process as a whole, respectively.

Bowes, P. C. (Joint Fire Research Organization, Borehamwood, England) "The Thermal Explosion of Solid Unstable Substances," *Joint Fire Research Organization Fire Research Note No. 788* (October 1969)

Section: G
Subjects: Organic peroxides; Thermal explosion; Unstable substances

Author's Abstract

The paper briefly reviews the thermal explosion model and summarizes a study of the thermal decomposition and thermal explosion of some solid organic peroxides. The object of the study has been to consider the use of the Frank-Kamentskii model of thermal explosion for predicting safe conditions for storage and transport of unstable substances in general.

It is concluded that experimental determination of the critical ambient temperatures for the thermal explosion of small charges of given shape and size is likely to be the most flexible and reliable procedure for predicting large-scale behaviour with the aid of the theoretical model. But any procedure should be accompanied by, at least, a rudimentary exploration of the decomposition kinetics of the material under examination in order to detect the presence of factors likely to interfere with the extrapolation to full-scale.

Bowes, P. C. (Joint Fire Research Organization, Borehamwood, England) "The Effect of Reactant Consumption on Substantially Sub-Critical Sub-Heating," *Joint Fire Research Organization Fire Research Note 821* (May 1970)

Section: G
Subjects: Self-heating; Spontaneous heating; Thermal explosions

Author's Summary

Measurements of the maximum temperature increase in self-heating solids under substantially sub-critical conditions provide useful estimates of rates of heat generation at different temperatures. The purpose of this paper is to calculate theoretically the extent to which these estimates are affected by consumption of reactant during self-heating.

It is confirmed that the effect of reactant consumption in this region is considerably less than its effect on the critical condition for thermal explosion. For systems having a heat of reaction high enough to permit sharply defined thermal explosion, the effect of reactant consumption on substantially sub-critical self-heating can be to reduce the maximum temperature by less than 10 percent.

Brookes, F. R. "The Combustion of Single Captive Particles of Silkstone Coal," *Fuel* **48,** 139–149 (1969)

Section: G
Subjects: Burning times; Coal; Particle burning; Silkstone coal

Abstract by Safety in Mines Research Establishment, England
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In this paper, experiments are described in which cine and streak photography were used in determining the mode of burning in air and the burning times of single captive particles in Silkstone coal, in the size range 124–850 μm diameter, subjected to radiant heat. The experiments showed that the particles swell to varying degrees depending on the method of heating and the particle size, after which the coke residues ignite. Moreover, the coke residues burn not as solid spheres with the particle diameter diminishing finally to zero, but in the form of hollow spheres. The duration of the coke-residue burning stage has been measured, and the results show reasonable agreement with the predicted values based on the theory of diffusion control. For comparison, measurements have also been made of the burning times of particles in the size range 210–355 μm, prepared from Silkstone coal previously devolatized in the absence of air.

Countryman, C. M., Palmer, T. Y., Storey, T. G., Bush, A. F., Leonard, J. J., Yundt, W. H. (Pacific Southwest Forest and Range Experiment Station, U.S. Forest Service, Berkeley, California) "Project Flambeau—An Investigation of Mass Fire, 1964–1967," *Final Report under Contract DAHC20-67-C-0149 for the Office of Civil Defense* (1969) Volumes I, II, III

Section: G
Subjects: Air flow; Convection columns; Fire behavior; Fire storms; Flambeau (Project); Flame zone temperature; Fuel moisture; Fuel weight loss; Heat flux; Mass fire

Authors' Summaries

Volume I.—**C. M. Countryman**

Project Flambeau was an exploratory study into mass fire behavior. The research was conducted by the Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture, for the Office of Civil Defense, U.S. Department of the Army, and the Defense Atomic Support Agency, U.S. Department of Defense. The objectives of Project Flambeau were to . . .

- Determine the minimum size of fire and fuel loading at which mass fire, and particularly fire storm effects, occur, so as to provide a "standard" mass fire for future and more sophisticated studies.
- Explore the instrumentation problem in mass fire research, and develop instrumentation for such experimental work.
- Acquire as much quantitative information as possible on fire systems, particularly in those areas of primary interest to civil defense problems.
- Test the validity of the descriptive model of a simple mass fire system.

Six experimental or test fires were burned at isolated sites along the California-Nevada border from 1964 to 1967 (Table 1).

TABLE 1
Experimental Fires Burned in Project Flambeau, 1964–1967, California and Nevada

Fire No.	Plot code No.	Date burned	Fuel bed spacing	Arrangement (rows)	Wind	Fuel moisture	Intensity rank[1]
			Ft.	*Ft.*			
1	760–1–64	1–31–64	115	3 by 3	Moderate	Moderate	3
2	760–2–69	5–15–64	25	6 by 6	Moderate	Dry	1
3	760–3–65	6–11–65	115	3 by 3	Strong	Dry	2
4	460–14–65	12–6–65	25	18 by 18	Light	Wet	6
5	460–7–66	6–14–66	25	15 by 16	Light	Dry	4
6	760–12–67	9–29–67	25	18 by 19	Moderate	Moderate to wet	5

[1] Based on flame height and fire activity in individual fuel beds.

In addition to these six test fires, preliminary fires were burned to study the suitability of available fuels, to check the validity of the "external look" approach to the study of fire behavior, and to gain insight into instrumentation needs of large test fires.

In the six test fires, multiple-fuel beds were used to simulate urban conditions. The fuel beds were built by arranging uprooted pinyon pine and Utah juniper trees in square piles covering about 2,000 square feet. Each pile of fuel was 46.7 feet on a side, averaged 7 feet high, and contained about 40,000 pounds of fuel (dry weight) Test fire sizes of 5, 15, 30, and 50 acres were arbitrarily selected. The plots, with 25-foot and 115-foot spacing between piles, were built for the selected fire sizes. Fires were started by electrically igniting spitter fuses and squibs.

Instrumentation was developed concurrently with burning of the test fires. It varied greatly in both kind and amount from fire to fire. Emphasis was placed on developing methods of directly and quantitatively measuring parameters of interest. In the "external" approach to study used in the Flambeau program, the parameters of interest were those concerned with the interactions of fire and environment and the changes in energy release rate with time.

The parameters measured in the test fires included (a) air flow in and around the fire area and pressure variations within the fire area; (b) thermal energy production, including mass loss rate of the fuel, temperature in the combustion zone, temperature of gases surrounding the combustion zone, and thermal radiation from the fire area; (c) gas composition, primarily concentrations of carbon monoxide, carbon dioxide, and oxygen within the combustion zone and in the "streets" between fuel beds.

Data collected were not primarily for the purpose of developing statistically valid cause-and-effect relationships. Rather the intent was to gather data which could provide the foundation for development of realistic theory on fire behavior and to provide guides to development of experimental studies, both in the field and in the laboratory. These studies would be aimed at solving fire problems with a reasonable expectation of deriving practical benefits. These objectives were largely accomplished.

Only six test fires were actually burned. And the tests were made under a limited range of fuel and environmental conditions. Data from the tests have yet to undergo rigorous analysis. Nevertheless, it is possible to draw some of the more obvious conclusions from the completed tests.

1. Fuel characteristics, including those associated with both fuel elements and fuel beds, are the major controlling factors in fire behavior. The burning fuel provides the basic driving energy for fire behavior phenomena associated with fire. How the potential thermal energy of the fuel is released may be affected in some cases by such environmental conditions as wind speed and air stability. In general, however, the thermal pulse produced by a given fuel bed will depend largely on the characteristics of the fuel and of the fuel bed itself.

2. Rate of thermal energy production is of primary importance in determining fire characteristics and behavior. The rate at which the thermal energy of fuel susceptible to combustion is produced is far more important than the size of the burning area. Close-spaced fuel bed fires in the Flambeau program varied in size by a factor of 11. However, air flow patterns, temperature, fire behavior, and noxious gas production were in general the same in the smallest as in the largest

fires. The lower limit of fire size in which mass fire characteristics will appear was not determined with certainty. Because of the major influence of fuel characteristics this limit probably varies with fuel type. In fuels such as were used in Flambeau test fires, mass fire characteristics can be developed in fires in the order of 100,000–550,000 square feet in area. Test results strongly suggest that mass fires can be developed in a smaller area.

3. Strong airflow and turbulence develop within the fire boundaries. In all test fires burned, the strongest air flow and turbulence were inside the fire boundaries away from major influence of ambient flow. In the multiple fuel-bed fires the increase in air flow into the fire area was significantly greater than that of ambient flow. Air speeds within the fire area, however, were several times greater than the air inflow at the fire periphery.

4. Radiation is of minor importance in fire spread outside of the fire boundaries. The lack of ignition by radiation outside of the fire boundaries was a marked characteristic of all Flambeau fires in this test series. Radiation as a factor in fire spread can be expected to become important only where spread by flame contact and firebrands is limited. For urban fires, of the type to be expected following nuclear attack, fire-induced turbulence within the area initially ignited will insure maximum flame contact and firebrand movement.

5. For multiple fuel-bed fires the position of a fuel bed in the array has only a minor effect on its thermal pulse pattern. In the mass loss experiment of Test Fire 6, only small differences were found in the mass loss rates for fuel beds in different positions. The differences that did appear seemed more closely related to variation in the circulation pattern within the fire area than to position of the fuel bed with respect to the fire center.

6. The Countryman descriptive model is a realistic portrayal of a stationary mass fire system. All six zones of the model appeared in two of the test fires. In other tests the convection column did not reach heights that permitted smoke fallout and convective development zones to develop. Fire behavior and associated phenomena were generally similar in the fuel, combustion, and transition zones for all fires that produced mass fire characteristics.

7. Wildland fuels may be used to simulate urban fires. Wildland and urban fuel beds are dissimilar and cannot usually be expected to produce similar fires in their natural state. But the thermal pulse produced by a burning fuel bed is dependent so much on fuel bed characteristics that it is possible to select and arrange wildland fuels to produce a thermal pulse that will be similar to that of an urban fuel, and to produce similar fire characteristics. Success in simulation will depend upon knowledge of burning characteristics of wildland fuels and thermal pulse characteristics of the urban fuel bed to be simulated.

8. Fire whirls are a consistent phenomenon in large and intensely burning fires. Fire whirls occurred in nearly all Flambeau test fires, and commonly occur in wildland fires. This phenomenon is of considerable importance in urban mass fire spread and in fire control activity. Fire whirls are likely to be of major importance in civil defense aspects of mass fire because of their destructiveness and their capability to rapidly spread fire and transport noxious gases.

9. Lethal concentrations of noxious gases occur within and adjacent to fires. High concentrations of carbon monoxide, carbon dioxide, and deficiency of oxygen were found in the combustion zone of Flambeau fires. Less severe concentrations appeared between the fires and on the fire edge. Since peak concentration of lethal

gases, minimum oxygen, and peak heat occurred at about the same time, their combined effect may be greater than any one alone. Also of significance is the long time duration of carbon monoxide concentrations within the fire area that are high enough to affect a person's judgment and action, although not directly causing permanent injury or death.

Volume II.—Catalogue of Project Flambeau Fires—**T. Y. Palmer**

This report summarizes, in catalogue form, the data available from nine experimental fires conducted by Project Flambeau from 1964 to 1967. The fires were burned as part of an investigation of mass fire sponsored by the Office of Civil Defense, Department of the Army, and by the Defense Atomic Support Agency, Department of Defense, Washington, D.C.

Project Flambeau was a research activity of the Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture, Berkeley, California. It had headquarters at the Station's Forest Fire Laboratory, Riverside, California. Before July 1966, Project Flambeau was known as the Fire Behavior Project of the Station.

The designations for the nine fires and the dates they were burned were:

Experimental Fire	*Date*
760–1–64	January 31, 1964
760–2–64	May 15, 1964
760–3–65	June 11, 1965
460–14–65	December 6, 1965
460–7–66	June 14, 1966
SR–3–67	June 8, 1967
SR–5–67	August 10, 1967
760–12A1–67	August 29, 1967
760–12–67	September 29, 1967

For each fire, this report provides information on (a) test data, (b) project number, (c) project officer, (d) types of measurements, (e) photography, (f) security clearance, (g) volume of records, (h) date of release, and (i) cooperative studies.

The following types of data were measured, recorded, and are available: fuel weight loss, flame temperature, air flow, differential and barometric pressures, fuel moisture, relative humidity, heat flux, gas temperature, soil temperature, snow melt measurements, thermal radiation, heat output, convection column, and weighing platform moisture.

The data available are on tabulated sheets, film, computer listings, slides, or strip charts. They are on file at the Forest Fire Laboratory, Pacific Southwest Forest and Range Experiment Station, P.O. Box 5007, Riverside, California 92507.

Volume III.—Appendixes. Three reports

"Preparation of Test Plots for Fire Behavior Studies Using Wildland Fuels to Simulate Urban Conditions"—**T. G. Storey**

Studies in forest fire behavior by the Pacific Southwest Forest and Range Experiment Station have included a series of experimental fires made for the U.S. Defense Atomic Support Agency and U.S. Office of Civil Defense. Piles of uprooted pinyon pine and Utah juniper were set up, dried, instrumented, and then burned at a test site along the California-Nevada border. The piles represented fuel loading and spacing of houses in residential areas of typical cities in the United States. In each plot, the piles were ignited simultaneously so as to obtain a high-intensity fire.

In the 1964–67 experimental fires, the Station used some unique methods to select the test site, clear the land, prepare the plots, and determine the amount of fuel. By using entire trees for fuel, including roots, the cost of gathering fuel was reduced markedly. This paper describes the methods used and includes recommendations of what might be done in future work of this type.

Candidate test sites within the pinyon pine-juniper type were chosen after a reconnaissance survey from light aircraft, study of aerial photos, and follow-up ground inspection. Two sites were selected: the 45,000-acre Basalt Site north of U.S. Highway 6 and west of Basalt, Mineral County, Nevada; and the 15,000-acre Mono Site south of California Highway 31, Mono County, along the California-Nevada border, and northeast of Lee Vining, California. After the sites were chosen, tree stands were tentatively matched with plot fuel requirements.

Trees in each of the 14 selected areas were lifted, transported, and piled to furnish the fuel for burning. The job of plot preparation was handled by a private contractor. The test fuel beds were built by arranging pinyon pine-juniper trees in piles covering about 2,000 square feet and standing 6 or 7 feet tall. After fuel piles were completed, they were left to dry. Plots were to be burned when their average moisture content approximated that of wood in buildings. Before burning, each plot was heavily instrumented to measure characteristics of the fire and its environment.

The following conclusions were drawn on the basis of the work done:

1. Experience to date in preparing, conditioning, and burning experimental fires using pinyon pine-juniper debris has been favorable. The debris dried rapidly, permitting early burning. Weather conditions were not particularly a problem in the field work.
2. Some difficulty was encountered in writing the clearing contract and communicating with prospective bidders so as to get the results wanted. In future work of this type, extreme care should be taken in writing the contract requirements so that they are unambiguous.
3. The existing tree weight-crown diameter relationships for pinyon pine and Utah juniper may be directly applicable to these and to other species of pinyon pine and juniper growing elsewhere in the Southwestern United States.
4. Good aerial photos are essential for selecting sites and prospective plot areas.
5. The technique of clearing and the individual types of equipment and equipment teams developed and used by the contractor appeared to be equal to the job.

Tree Weights and Fuel Size Distribution of Pinyon Pine and Utah Juniper—
T. G. Storey

To aid in timber cruising for preparation of test plots and in interpretation of fire behavior, we gathered information on fuel weight and size distribution of pinyon pine and Utah juniper trees. This paper describes how trees of these two species were selected and sampled at the test sites, the analytical procedures used, and the results obtained in relating weight of fuel to size and to dimensions, and in determining distribution of fuel weight.

Sample pinyon pine trees were selected from three sites in the study areas: Pizona Site, on the Inyo National Forest, Mono County, California; Basalt Site No. 1, Mineral County, Nevada; Basalt Site No. 2, Toiyabe National Forest, Nevada; and Mono Site, Mono County, California.

On most sites, trees were stratified into four broad stem-diameter or crown-diameter classes to cover the range in tree sizes found. Trees were selected randomly from each diameter class in proportion to the frequency of trees in the class. Each sample tree was photographed; measured for height, maximum crown diameter, and average crown diameter; uprooted; and weighed.

A process of data plotting and curve-fitting indicated that tree weights of pinyon pine was correlated with each of the four independent variables studied: maximum crown diameter, average crown diameter, tree height, and stem diameter at 1 foot. Regression equations were computed for each of the four relationships and the coefficient of determination and standard error of estimates for each were calculated. Essentially the same type of analysis used for pinyon pine was applied to Utah juniper with similar results. A similar curve was found to apply for estimating ovendry crown weight and ovendry root weight from each of the same four variables. A regression equation also was computed for ovendry root weight on ovendry tree weight.

On the basis of the finding, we concluded that:

1. Dry tree weight, dry crown weight, and dry root weight are closely correlated with maximum crown diameter, average crown diameter, and stem diameter at 1 foot for pinyon pine, and with maximum crown diameter and average crown diameter for Utah juniper, which has multiple stems.
2. About 25 percent of the total dry weight of small pinyons may be in the needles; another 25 percent is in twigs and rootlets $\frac{1}{2}$ inch or less in diameter.
3. The fuel size distribution of juniper roots was not determined, but sample data on the total root weight of juniper are available. An estimate of the distribution of this weight, by size class, can be obtained by applying the data on distribution of pinyon roots.
4. The fuel size distribution curves for the small pinyon and small juniper crowns paralleled one another closely at fuel diameters larger than $\frac{1}{4}$ inch.
5. Fuel size distribution among branches of identical girth from larger trees of either species appears to vary only slightly.

Gas Analyses in Large Fire Experiments—**A. F. Bush, J. J. Leonard, and W. H. Yundt**

Large experimental fires make it possible to measure fire characteristics. Such fires allow a range of prescribed initial conditions, such as fuel moisture, loading, and geometry. They may be instrumented to yield measurements for evaluation of fire behavior and environmental effects.

In recent experiments, a limited program of gas sampling and analysis was carried out to provide some of the desired data on life hazard in the open (fuel bare) regions between piles or burning units and in regions where shelter location may force a reliance on ventilation. More recent experiments were instrumented expressly to provide further life hazard information in the zone of most probable human exposure.

This paper reports data from 13 experimental fires—six from the series 460, Mono County, California and 760, Mineral County, Nevada, and ranged in array size from 1 to 342 piles. Each pile weighed about 20 tons, and measured 46.7 feet square, and 7 feet tall. Fuel was primarily pinyon pine and Utah juniper trees. Results are also reported for four fires from series 380 and two from series 428, described as heavy fuel plots and light fuel plots. One experiment reported is a two-story house fire.

The sampling system used in Test Fire 760–12, burned on September 29, 1967, consisted of a bank of continuous analyzers sequencing six inlets. Gases from the inlets were drawn through separate tubes out of the fire to the instrument trailer about 400 feet away. Pressure in the six lines at the points of sample removal were kept constant.

The gas sampling equipment used in all experimental fires except 760-12 involved three separate types. The continuous sampling system had a main pump to draw samples through aluminum tubing. Two instrumental analysis systems drew their samples from the main line. The second system, sequential grab samplers, consisted of sets of five 300-cc. double stop-cock Pyrex gas bottles which were evacuated to 1 mm Hg or less before the fire and opened remotely at selected times by electric solenoid valves. The third system, integrating samplers, consisted of a set of six midget impingers, a self-contained pumping system, and a gas collection reservoir. The pumps draw sample gases through each of the impingers at a known flow rate between 0.5 and 1.0 liters per minute.

Systems developed to sample and analyze gases from experimental fires provided data that appear to be consistent with the general pattern of behavior of the fires and with other data collected. The capability of the systems used in fires before 760-12 was limited by the amount of continuous analysis equipment available, but it was partially remedied by the development of more sophisticated devices in later fires.

On the basis of the findings, the following conclusions can be drawn:

1. Gas analysis data is of importance in defining fire behavior, and comparing between experimental fires, in evaluating mass fire-related hazards, and in testing and providing valid data for fire models.

2. The measurement of water vapor concentration is essential to an understanding of mass fire, from the standpoint of defining internal environmental conditions, defining human exposure, and as a means of relating the combustion process to fuel parameters and true energy release rate.

3. Dilution ratios based upon carbon dioxide concentrations or other gas component measurements can provide broad insight for study of interactions within the mass fire system and may be used as the basis for empirical relationships between measurable parameters and complex effects associated with them. In addition, dilution ratios may provide a basis, with other measurements, for the understanding of mass transport in the fire environment.

4. Smoke analyses are required in order to better understand the gross combustion process, and to evaluate hazard to human life. Photomicrographs of particulate material in the atmosphere of three fires are shown. These give indication of the

nature of the suspended residue left in the air by combustion of forest and urban fuels.

5. Analyses of gases in the streets of large experimental fires to date suggest that sufficient oxygen for survival is available at ground level in such locations and that noxious gas concentrations are generally below hazardous levels over most of the fire history. An insufficient data base exists at present for extrapolation of this conclusion to analogous urban areas or very large mass fires.

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Sections: G, H
Subjects: Absorptance; Absorptance to emittance ratio; Accommodation coefficient; Alloys; Ceramics; Cermets; Coatings; Composites; Compounds; Critical evaluation; Data analysis; Data compilation; Data synthesis; Data tables; Diffusion coefficient; Elements; Emittance; Gases; Graphites; Information storage and retrieval system; Intermetallics; Liquids; Metals; Mixtures; Molten metals; Nonmetals; Paints; Polymers; Prandtl number; Recommended reference values; Reflectance; Refractories; Solids; Semiconductors; Semimetals; Specific heat; Standard reference data; Surface tension; Systems; Thermal conductivity; Thermal contact resistance; Thermal diffusivity; Thermal linear expansion coefficient; Thermal volumetric expansion coefficient; Thermophysical properties; Transmittance; Viscosity

Author's Summary

This technical report covers work in a continuing systematic program on the thermophysical properties of materials involving the literature search, acquisition, codification, and organization, and data extraction, compilation, evaluation, correlation, analysis, and synthesis, the preparation of "intermediate tables" presenting the total available experimental information, and the final preparation of internally consistent tables of "best data" referred to as "Tables of Recommended Reference Values." The work reported on consists of both data tables projects and scientific documentation efforts. The data tables projects are on the thermal conductivity, specific heat, thermal radiative properties (emittance, reflectance, absorptance, transmittance), thermal diffusivity, and thermal linear and volumetric expansion of elements, ferrous and nonferrous alloys, intermetallic, semiconducting, and nonmetallic compounds, cermets, ceramics, mixtures, composites, systems, polymers, etc., and on the thermal conductivity, specific heat, and viscosity of fluids and fluid mixtures. Property data are presented in both tabular and graphical forms, with accompanying tables giving specifications and characterizations of the test specimens for the data. The resulting data tables are disseminated at large through the 13-volume **TPRC DATA SERIES** published commercially.* This report does not contain the completed thousands of data sheets, but does reproduce in the Appendix, the Table of Contents and the Grouping of Materials and List of Figures and Tables for each of the first 7 volumes (which contain over 8000 pages) of the **TPRC DATA SERIES** to show the scope of their coverage. In scientific documentation, the scope is broader. TPRC covers all materials and maintains cognizance over 16 thermophysical properties (six more than mentioned above). There are now 55700 references in TPRC's automated Information Storage and Retrieval System. The resulting information on research literature is disdeminated through the **THERMOPHYSICAL PROPERTIES RESEARCH LITERATURE RETRIEVAL GUIDE**, published commercially.

* See page 273.

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Section: G
Subjects: Gap, safe; Quenching limits

Abstract by Safety in Mines Research Establishment, England
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The maximum experimental safe gap for a combustible gas or vapour is normally determined with a standard 8-litre spherical explosion vessel with equatorial flanges. Methods of predicting the safe gap for an untested fuel can be based on (1) a comparison of the molecular structure of the fuel with the structure of tested compounds, (2) a correlation with a function derived from the activation energy, or the flame temperature at the lower limit of flammability, and (3) correlation with the minimum igniting current.

Shelukhin, G. G., Buldakov, V. F., and **Belov, V. P.** (Leningrad) "Experimental Study of the Process of Combustion of Heterogeneous Condensed Systems," *Physics of Combustion and Explosion* **5**, 41–51 (1969). In Russian

Section: G
Subjects: Condensed systems; Heterogeneous combustion

Authors' Summary—Translated by L. Holtschlag

New results are obtained for the combustion of heterogeneous condensed systems (mechanical mixture of powdered oxidizer and infusible high-polymer binder), and for their combustion rates, in a broad pressure range, from vacuum to 100 bars. The samples were rectangular (3 cm×1.5 cm) and 0.2 cm to 1 cm thick. The temperature field in the gas phase was determined by the optical color method. The experimental optical apparatus is illustrated and the technique is described. The combustion of a separate local zone is essentially nonstationary. The time of layer preparation for burning is governed by the time of formation of the binder gasification zone, which is critical. When it is reached the heat received in the gasification zone exceeds the heat released, leading to an abrupt increase in temperature and burnup of the oxidizer crystals, i.e., to completion of transition of the solid mass to the gaseous state. The pattern of combustion in the gas phase varies with varying pressure, but the more typical features of the combustion process are maintained at all pressures, the most prominent feature being the emission of individual rays from each oxidizer center and from the adjacent binder center; the ray width is equal to the size of the center. Thus, studies of the gas phase confirmed the local oscillatory nature of the combustion of heterogeneous condensed systems and emphasized the interrelation between the condensed and gaseous phases.

Vodvarka, F. J. (IIT Research Institute, Chicago, Illinois) "Firebrand Field Studies," *IIT Final Technical Report J 6148, Office of Civil Defense Contract N00228-68-C-2686, Work Unit 2539B, Task Order 2530 (68)* (September 1969)

Section: G
Subject: Firebrands

Author's Summary

Five residential structures were free-burned to obtain data on firebrand production and transport. Two of the structures were intentionally damaged with explosives to simulate blast damage. Thin sheets of polyethylene were distributed downwind of the burning buildings to record the locations and sizes of the falling brands. Only those brands hot enough to melt through the plastic sheets were recorded by this procedure. The brand area was taken to be the same as the area of the hole in the sheet. Brand sizes ranged from smaller than a matchhead to 15 sq. in.

In general, the procedure was successful. The number of plastic sheets used proved to be insufficient because of the variability of the wind direction and the low firebrand fallout densities (firebrands per unit ground area) at large distances from the fire. This introduced some uncertainty in the measured firebrand densities as functions of downwind distance. Nevertheless, these densities should provide useful estimates until more information is available.

Because of the uncertainties in the firebrand density distributions as well as the total area of firebrand deposition, no attempt has been made to calculate the total firebrand production from the fires. However, the size distributions of the brands deposited at various locations are quite consistent and understandable in terms of the building characteristics. The fire experiment in one building closely duplicated the conditions of a laboratory experiment on firebrand generation, and the resulting firebrand size distributions for the two experiments were quite similar.

The differences in size distributions of the firebrands from the five buildings confirm laboratory findings concerning the effects of construction and building condition on the sizes of brands produced. In both field and laboratory experiments, it was found that the longer a roof remains intact during the fire, the greater is the fraction of small brands produced. Thus, heavy roof construction, low combustibility roof coverings and low buildings favor the production of small brands, while light roof construction, combustible shingles, tall buildings, and prior blast damage favor production of large brands. This is of particular significance, since laboratory findings indicate that brands larger than 1 sq. in. are the most hazardous because of their inherent ability of self-reinforced glowing combustion.

Three fire officers were retained as consultants to report on firebrand activities observed at accidental fires. The areas covered by these officers were: (1) a densely populated urban area, (2) a metropolitan suburban area, and (3) a rural community area. During the study only two accidental fires were reported with significant firebrand production. Both were large fires which burned out of control for long periods of time. One of the consultants also reported firebrand activity at two fires set intentionally for demolition of residential type structures. The lack of firebrand activity in the majority of accidental fires is attributed to effective fire fighting which prevents roof penetration.

Firebrand fallout densities determined by inspection of the ground after the four fires had been extinguished or burned out appeared to be greater than those in the experimental fires. This is believed to be due to the higher wind velocities and to the use of water spray for protection of exposures. However, there is no way of knowing how many brands were burning or could have caused ignitions. It was concluded that sound data on the numbers and sizes of active firebrands cannot be obtained from accidental fires. However, if data were collected on firebrand ignitions associated with a large number of fires, significant statistical analysis could be made. This would require extensive data collection efforts encompassing a large geographic area because the occurrence of such ignitions in any given locality is rare.

A questionnaire concerning the occurrence of firebrands was sent to 1600 fire officers in the United States and 475 replies were received. In total, 267 (56 percent) of the respondents reported the occurrence of firebrands. Of these 200 had observed ignition of other combustibles by firebrands. The most frequently identified source of firebrands were roofing materials, although structure and contents were identified frequently enough to be significant. The results of the questionnaire indicate that roofs are the most susceptible to ignition by firebrands, although other combustibles, particularly vegetation, were often ignited.

Geographically, the mountain states provided the fewest replies, and those indicated the lowest frequency of occurrence of firebrands. The remaining sections of the country all indicated about the same degree of occurrence of firebrands.

Masliyah, J. H. and **Steward, F. R.** (University of New Brunswick, Canada) "Radiative Heat Transfer from a Turbulent Diffusion Buoyant Flame with Mixing Controlled Combustion," *Combustion and Flame* **13** (6), 613–625 (1969)

Sections: G, I
Subjects: Radiant heat; Turbulent flame

Reviewed by J. M. Singer

A simplified mathematical model of a turbulent buoyant diffusion flame above an open liquid fuel source is described, which makes possible computations for the radiative flux density distribution on a horizontal plane around the base of the flame, and the liquid fuel burning rate. Two zones are assumed for convenience: the first extending from the liquid fuel source up to the point of stoichiometric composition (the bottom combustion region), and the second from this boundary to infinity (the upper hot plume region). A number of other assumptions are made to further simplify the treatment, with recognition and discussion of their inadequacies, especially the assumptions of negligible radiation from the flame (gray flame emission), and of instantaneous mixing and reaction of entrained air in the bottom zone, keeping the temperature uniform throughout this region.

Profiles of the jet radius as a function of axial distance and the concentration of the source jet fluid throughout the jet were obtained for the combustion and hot gas plume regions as prerequisite to the computation of radiative emission throughout the flame. The radius and concentration profiles were derived from force balance equations that equated the change in jet momentum across a differential element with the buoyancy force acting on the jet fluid. The treatment was simplified by introducing dimensionless variables of momentum and mass flux into the dimensionless continuity equation and the force balance and mixing equations. An important parameter, the axial height (H) of the combustion zone at stoichiometric mixing is shown to be:

$$H = CA^{1/5}F_m^{2/3}$$

where $A = [12k\rho_0'/5(1-\rho_0')\pi^2(\rho_0')^2 g]$
$C = 5[5(\rho_0')^{2/5}/4k][(r_s+1)^{2/5}-1]$
F_m = fuel mass flow rate throughout the source
$2k = 0.1125$, the mixing coefficient for circular turbulent jets
ρ_0' = (density of source fluid/density of ambient fluid)
g = gravitational constant
r_s = mass of air required for stoichiometric mixing (lb air/lb total)

The jet radius profile in the lower combustion zone is given by

$$y' = y/y_0 = (4kx'/5\rho_0'^{1/2}) + C_b^{1/5}/(\rho_0')^{1/10}$$

where $C_b = 12k\rho_0'(Fr)/5(1-\rho_0')$; $(Fr) = u_0^2/gy_0$, the Froude number;

x' = the axial distance along the flame/y_0;

y_0 and y = radius of source fuel and flame respectively; and u_0 = velocity of fluid in the flame at source.

The concentration of source jet fluid throughout the lower jet is given by

$$f = \rho_0'/[4kx'/5C_b^{1/5} + \rho_0'^{2/5}]^{5/2}$$

where f = concentration of original source fluid in flame, (lb/lb).

The radiative analysis is also based on several simplifying assumptions such as gray flame emission (emission independent of wavelength), negligible scattering of emission, emission proportional to concentration of original source fluid at that point, and black body receiving surface. Radiant emission from the carbon particles in the bottom and top zones to the surface surrounding the base of the flame were derived from equations that are based essentially on the parameters: KH, ρ_0', or T_0/T_a, r_s, and z/H where KH is the "darkness factor" of the flame, K is the proportionality constant defining the absorption coefficient; T_0 = absolute temperature of the liquid source; T_a = absolute temperature of the hot gas; and z = distance from jet axis on surface surrounding the base of the flame.

Calculated numerical results are given of the radiant flux density distribution along the base for various values of the "darkness factor" KH for a combustion zone temperature of 2300°R, and for various values of the combustion zone temperature with an intermediate KH value of 6.5. With these results, it was possible to predict the burning rate of a liquid fuel source of a given diameter and fuel type, using a graphical solution. Assuming that one to five percent of the fuel will form carbon particles, and using a "degree of darkness" computed by the empirical method of Hottel and Sarofim,[1] the computations of fuel mass flow rate versus source diameter agreed reasonably with the data of Blinov and Khudiakov.[2] The agreement seems to indicate that radiation is the major mechanism of heat transfer for liquid fuels in pan diameters of one foot or more. It is noted that for small pans (diameters of an inch or less), the major mechanism appears to be conduction down the side of the pan.

References

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2. Blinov, V. I. and Khudiakov, G. N.: *Dokl. Akad. Nauk S.S.S.R.*, Vol. 113 (1957), p. 1094.

H. Chemical Aspects of Fires

Beall, F. C. and **Eickner, H. W.** (Forest Products Laboratory, U.S. Forest Service, Madison, Wisconsin) "Thermal Degradation of Wood Components: A Review of the Literature," *U.S.D.A. Forest Service Research Paper FPL 130* (May 1970)

Section: H
Subjects: Pyrolysis; Thermal degradation; Wood

Authors' Summary

This review of literature was developed as part of an investigation to analyze the thermal degradation reactions of wood, cellulose, hemicelluloses, and lignin. Two methods are emphasized: thermogravimetric analysis and differential thermal analysis. The process of general thermal degradation for wood is discussed and is followed by specific review of the literature on thermal analysis studies of wood and its components.

Contents:

Woolley, W. D. and **Wadley, Ann I.** (Joint Fire Research Organization, Borehamwood, England) "Experimental and Theoretical Studies of the Dehydrochlorination of PVC in Air and Nitrogen," *Joint Fire Research Organization Fire Research Note 795* (January 1970)

Section: H
Subjects: Combustion products; Dehydrochlorination; Hydrogen chloride; Poly (vinyl-chloride); PVC; Toxic gas

Authors' Summary

The release of hydrogen chloride from the thermal decomposition of a sample of a commercial rigid PVC has been studied in air and nitrogen between 200 and 300°C. It is shown that the dehydrochlorination can be represented by a $\frac{3}{2}$ order decomposition with activation energies of 36.1 and 41.5 K cal mole^{-1} in air and nitrogen, respectively. The report explains how this kinetic data can be used to predict the total release of hydrogen chloride as a function of time from the decomposition of PVC during either isothermal conditions or non-linear temperature increments as in fires. A comparison is shown between the experimental and calculated release of hydrogen chloride during a temperature programmed experiment between 200 and 300°C.

I. Physical Aspects of Fires

Adams, F. C. and **Day, T. V.** (Joint Fire Research Organization, Borehamwood, England) "The Thermal Movement of Concrete Floor Units under Fire Conditions," *Joint Fire Research Organization Fire Research Note 816* (April 1970)

Section: I
Subjects: Building, industrialized; Concrete, reinforced, expansion; Fire resistance; Floors; Thermal movement

Authors' Summary

With some forms of precast building construction the failure of the structural element junctions may cause premature collapse of the building in the event of fire. There is no equipment that can assess under fire conditions the behaviour of a building system and for this reason the equipment normally used for fire resistance tests on individual elements was utilised. The experiment was designed to provide data on the movement that could be expected in concrete floor slabs and to assess whether failure at the supporting walls could result.

Hinkley, P. L. (Joint Fire Research Organization, Borehamwood, England) "A Preliminary Note on the Movement of Smoke in an Enclosed Shopping Mall," *Joint Fire Research Organization Fire Research Note 806* (March 1970)

Section: I
Subjects: Smoke, escape means; Smoke, shopping mall; Smoke, spread

Author's Summary

The design of escape routes from enclosed pedestrian shopping malls in large town centre developments would be facilitated by a knowledge of the likely rate of spread of smoke should a fire occur. This note discusses the spread of smoke along a mall in the light of a tentative theory (given in detail elsewhere). Assuming the theory to be correct a fire 2 m×2 m base area would smoke-log a mall 6 m wide and 3 m high for 70 m in both directions in about $2\frac{1}{2}$ minutes. A fire "flashing over" in a small shop could smoke-log the mall for 200 m in both directions in the same time.

Further work to verify the theory will be carried out.

Heselden, A. J. M. and **Hinkley, P. L.** (Joint Fire Research Organization, Borehamwood, England) "Smoke Travel in Shopping Malls—Experiments in Co-operation with Glasgow Fire Brigade. Part 1," *Joint Fire Research Organization Fire Research Note 832* (July 1970)

Section: I
Subjects: Smoke, escape means; Smoke, shopping malls; Smoke, spread; Smoke, tunnel

Authors' Summary

With the object of estimating the hazard from the smoke-logging of a pedestrian mall measurements of the rate of travel of smoke and the depth of the smoke layer have been made in a disused railway tunnel 600 m (2000 ft) long. The ends were open or closed and three sizes of fire were used. The smoke layer, at first dense and well stratified, travelled at a speed in the order of 1 m/s (3 ft/s). Both the speed of travel of the smoke and the thickness of the layer (which both increase with the size of the fire) agree with a theory recently developed.

Thinner smoke was formed under the dense layer, sometimes causing smoke-logging to the floor, particularly at the ends of the tunnel, the closed end situation being particularly bad.

Hinkley, P. L. (Joint Fire Research Organization, Borehamwood, England) "The Flow of Hot Gases along an Enclosed Shopping Mall—A Tentative Theory," *Joint Fire Research Organization Fire Research Note 807* (March 1970)

Section: I
Subjects: Smoke, escape means; Smoke, shopping mall; Smoke, spread

Author's Summary

The flow of smoke and hot gases in an enclosed shopping mall is discussed in general terms in another note. The present note gives the theoretical background of that discussion which is based to a large extent on the theory of "gravity currents" investigated by Benjamin.

Formulae have been derived for calculating the rate of spread of a layer of hot gases beneath the ceiling and the depth of the layer. The depth of the spreading layer cannot exceed half the height of the mall but smoke can mix into the cold air flowing towards the fire thus effectively deepening the depth of smoke.

The formulae show encouraging agreement with the results of a large-scale experiment on smoke spread carried out in Japan but more experimental work is required to establish their validity. If the theory is correct it would be necessary to install a ventilation system to ensure that occupants can escape from a mall before being overtaken by smoke in the event of fire, even if a sprinkler system is fitted in the shops bordering on the mall. Should the sprinkler system fail, smoke could spread rapidly along the mall (e.g., 100 m in 30 s).

Lambert, N. K. and **Quince, B. W.** "The Evaporation of Falling Water Droplets," *Journal of Colloid and Interface Science* **30,** 146–147 (1969)

Section: I
Subjects: Droplet evaporation; Evaporation, of drops; Fuchs' equation

Abstract by Safety in Mines Research Establishment, England
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A formula for calculating the evaporation of droplets based on Fuchs' equation is given. Calculated and experimental values of the evaporation of falling water droplets in a limited range of environments are shown to be in reasonable agreement.

Leach, S. J. "Stratification and Mixing of Fluids of Different Densities," *Symposium on Chemical Process Hazards, Manchester, England, 1967*, 17–25 (1968)

Section: I
Subjects: Mixing; Stratification

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In an earlier publication (Bakke and Leach, 1965) the equations of motion and turbulent diffusion of a buoyant boundary layer were solved by introducing an eddy diffusivity dependent on the Richardson number. Experimental results obtained with methane roof layers (in air) and brine floor layers (in water) showed good agreement with theory. The present paper outlines this work and discusses the conditions under which the effects of buoyancy are significant and how these effects can be overcome. Consideration is given to limiting the flammable volume produced by the mixing of a layer of flammable gas with air. When the characteristics of the main flow cannot be arranged to give adequate mixing it is possible to increase the mixing rate by the use of baffles and by recirculation. The practical application of these methods is discussed.

Lee, Shao-Lin and **Hellman, J. M.** (State University of New York at Stony Brook) "Study of Firebrand Trajectories in a Turbulent Swirling Natural Convection Plume," *Combustion and Flame* **13**(6), 645–655 (1969)

Section: I
Subjects: Convection; Firebrands; Plumes; Turbulence

Reviewed by A. Strasser

The behavior of firebrands in a turbulent, swirling, natural convection plume was examined theoretically and experimentally. Presence of such violently fluctuating flow fields in the neighborhood of large fires is regularly observed. Transport of firebrands to neighboring, unignited areas of fuel bed is one of the major mechanisms of fire spread. Tarifa and co-workers[1] first studied firebrand properties in a wind tunnel and determined the effect of size, shape, and kind of wood on their range. Similarly, the goal of the present study was to determine the effect of the parameters which controlled the trajectories and behavior of firebrands but with the additional complications imposed by the dynamics of natural convection plumes. The complexity of the problem led to the formulation of simplifying assumptions including (1) that the concentration of particles was low enough so that the fluid flow field was not affected by the particles, (2) that the firebrand was spherical and would remain spherical during burning without change in density, (3) that the burning rate remained constant during burning, depending only on the firebrand material, (4) that the drag coefficient remained constant despite the partial burning, and (5) that the boundary layer on the particle was turbulent. These assumptions were consistent with Tarifa's.

The equations of motion for the firebrands were written under these assumptions. The fluid velocity field was described on the basis of previous work by Lee[2] and the trajectory was obtained by applying Newton's second law to the particle. Despite the fact that the mass of the particle depends on the time, the second law could still be written in the simplified $F = ma$ form because of the assumption that the combustion rate is uniform over the firebrand surface. Following Tarifa,[1] this implies that the mean relative velocity of the gases leaving the firebrand is zero and the change of momentum of these gases does not appear in the equation.

Once the plume parameters were specified, trajectories were calculated by assigning values to the applicable firebrand parameters (buoyancy, burning rate, and initial diameter) after the equations were integrated numerically. Initial position conditions were chosen and the initial velocity of the particle was considered to be the velocity of the fluid at that point, under the assumption the particle, having traveled near the fire whirl, would attain the fluid velocity, approximately at the point of injection. After injection, the trajectory of the firebrand is dependent on the forces acting on it, which are drag force, gravity, and centrifugal force. Since the drag force is proportional to the cross-sectional area of the particle and the body forces are proportional to the volume of the particle, the burning of the particle will have a greater effect on the body forces than on the drag forces.

Families of curves representing a number of the calculated trajectories in dimensionless form were presented with particle altitude, radial distance, and angular speed as functions of time from injection into the swirling plume. Parameters varied and included initial radial distance, burning rate, buoyancy, and particle size. Resultant motions of the particles, based on these curves, indicate the various types of possible paths. Depending on parameter values, the burning particle may be centrifuged almost immediately or travel upward and then down, falling to the ground at some distance from the base of the plume or burn out before striking the ground.

These analytical conclusions were tested experimentally in a small-scale apparatus. Particles used to simulate firebrands were flat plates consisting of punch-outs from computer cards or small spheres consisting of poppy seeds or certain types of breakfast cereal. The flat-plate, low drag particles proved to be more stable in the plume than the spherical, high drag particles. The general shape of the trajectory depended on a balance of drag and centrifugal forces in the radial direction. The magnitude of these forces was a function of the location of the particle in the plume. The experimental results qualitatively verified the general assumptions made by the theoretical study in that the drag and body forces produced trajectories that were of the types predicted.

References

1. Tarifa, C. S., Del Notario, P. P., and Moreno, F. G.: "On the Flight Paths and Lifetimes of Burning Particles of Wood," *Tenth Symposium (International) on Combustion*, 1021–1037 (1965).
2. Lee, S. L.: "Axisymmetric Turbulent Swirling Natural Convection Plume," *J. Appl. Mech., Trans. Am. Soc. Mech. Engrs., Series E 33*, 647–655 (1966).

Powell, J. H. and **Simpson, S. P.** "Theoretical Study of the Mechanical Effects of Water Jets Impinging on a Semi-Infinite Elastic Solid," *International Journal of Rock Mechanics and Mining Sciences* **6**, 353–364 (1969)

Section: I
Subjects: Elastic impact; Jets; Mechanics of jets

Abstract by Safety in Mines Research Establishment, England
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A method is developed for determining the stress distribution in an elastically homogeneous semi-infinite solid when its plane-free surface is subjected to an axially symmetrical load. This method is used to determine the stress field induced in an elastic solid by a water jet impinging on its surface. The theoretical stress distribution is used, together with a fracture criterion derived from the Griffith theory of crack propagation in solids, to predict the rock-cutting properties of water jets in relation to the mechanical strength of the target rock. The theoretical predictions are compared with experimental findings.

Shakeshaft, Margaret (Joint Fire Research Organization, Borehamwood, England) "S.I. Units and Their Use at the Fire Research Station," *Joint Fire Research Organization Fire Research Note 811* (March 1970)

Section: I
Subjects: S.I. units; Units

Author's Summary

The note explains the S.I. units and gives a list of those which are to be commonly used by the Fire Research Station, with other units that at present may be used as well. A list of conversion factors is also given.

J. Meteorological Aspects of Fires

Nielsen, H. J. (IIT Research Institute, Chicago, Illinois) "Origin and Properties of Fire Whirls," *Report under Contract N00228-67-C-2760 to Office of Civil Defense* (August 15, 1969)

Sections: J, I
Subjects: Atmospheric vortices; Mass fire; Urban fires; Fire whirls; Vortices

Author's Abstract

To determine the origin of fire whirls in fires, the origin of the vertical vorticity required to sustain them was investigated. It was found that the vertical vorticity developed by the bending upward of the horizontal vortex lines of the ambient wind boundary layer is greater than that produced by other mechanisms. The intensity and distribution pattern of the vorticity is also in agreement with the circulatory flow found to exist in experimental fire wind data. A method for estimating the intensity of fire whirls in urban fires is given. This is based on the way the vorticity production scales with fire size and on existing analyses of the properties of convective vortices.

Vines, R. G. (C.S.I.R.O., Melbourne, Victoria, Australia) "A Survey of Forest Fire Danger in Victoria," *Australian Forest Research* **42,** 39–44 (1969)

Section: J
Subjects: Fire hazards; Forest fires; Victoria, Australia

Author's Summary

An attempt has been made to derive forest Fire Danger Ratings in Victoria, year by year, from a study of the weather records for Melbourne. Comparative estimates obtained using McArthur's Fire Danger Meter correlate reasonably well with the known fire records of past seasons.

Severe fire years are determined mainly by the incidence of days of "Extreme" Fire Danger. On the average, potentially bad fire seasons seem to occur about once every three years. Bad fires have taken place in Victoria approximately every six or seven years and, so far in the present century, this has led to an apparent pattern of very bad fires every thirteen years.

K. Physiological and Psychological Problems from Fires

Chambers, E. D. (Joint Fire Research Organization, Borehamwood, England) "Exeter Chip Pan Safety Campaign: Effect on Fire Frequency," *Joint Fire Research Organization Fire Research Note 801* (March 1970)

Sections: K, A, L
Subjects: Cooker; Cost benefits; Domestic; Fire prevention; Fire statistics; Time series

Author's Summary

Distribution of a leaflet on chip pan safety is, using a control chart technique, shown to have resulted in a statistically significant reduction in fire frequency. The maximum effect appears to have been about eighteen months after the campaign.

Chambers, E. D. (Joint Fire Research Organization, Borehamwood, England) "Make Leicester Fire-Safe Campaign: Statistics of Fires in Dwellings," *Joint Fire Research Organization Fire Research Note 802* (February 1970)

Sections: K, A, L
Subjects: Correlation; Cost benefit; Fire prevention; Fire statistics; Publicity; Time series

Author's Summary

Dwelling fire statistics were examined for a period before and after an intensive generalised fire prevention campaign. Both frequency and average size appeared to have been reduced for a few months afterwards.

Critchlow, A. and **Maguire, B. A.** "Pneumoconiosis Research at the Safety in Mines Research Establishment," *Transactions of the Institution of Mining and Metallurgy (Section A)* 77, 159–166 (1968)

Section: K
Subjects: Dust; Lungs; Pneumoconiosis; Respiratory problems

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Research on many aspects of pneumoconiosis control in mines is being carried out by laboratories and organizations in many countries. The Safety in Mines Research Establishment's work in this field is concerned mainly with (1) the physics of respirable dust, and the design of dust-sampling instruments, (2) the analysis of human lung material and (3) the analysis of the results of experiments in which laboratory animals are exposed to high airborne-dust concentrations. This paper describes SMRE's work on pneumoconiosis, and relates this work to the general context of coal-workers' pneumoconiosis.

L. Operations Research, Mathematical Methods, and Statistics

Ministry of Technology and Fire Offices' Committee Joint Fire Research Organization "United Kingdom Fire and Loss Statistics, 1968," *London: Her Majesty's Stationery Office* (1970)

Section: L
Subjects: Brigade reports; Fire loss; Statistics, U.K., 1968

Statistical analysis of reports of fires attended by fire brigades in the United Kingdom during 1968.

Chambers, E. D. (Joint Fire Research Organization, Borehamwood, England) "Street Numbers of Houses where Fires Occur," *Joint Fire Research Organization Fire Research Note 798* (February 1970)

Section: L
Subjects: Area; British; Comparison; Distribution; Domestic; Fire prevention

Author's Summary

Selecting houses with given street numbers is shown to be a convenient basis for experimental approaches to fire prevention.

Chambers, E. D. (Joint Fire Research Organization, Borehamwood, England) "Gas Explosions in Dwellings, 1969: Material Damage and Injuries," *Joint Fire Research Organization Fire Research Note 826*

Section: L
Subjects: Casualties; Comparison; Distribution; Domestic; Gas explosion; Loss

Author's Summary

Comparison of fire brigade reports of town and natural gas explosions suggests that the distributions of material damage are similar, and that an average of about 0.4 persons are injured per reported incident.

Chandler, S. E. (Joint Fire Research Organization, Borehamwood, England) "Fire Deaths in the Fourth Quarter of 1969," *Joint Fire Research Organization Fire Research Note 799* (March 1970)

Section: L
Subjects: Deaths, 1969; Fatalities; Fire statistics

Author's Summary

A preliminary survey shows that 202 persons died in fires in the fourth quarter of 1969. Of these, 171 were in England and Wales, 28 in Scotland, and three in Northern Ireland. Revised estimates for the first three quarters are 311, 173, 103 respectively, giving a total of 789 for the year, slightly below last years total of 865.

Eleven people died in a hotel fire at Saffron Walden. Two firemen were killed at fires, one in England and one in Scotland.

Chandler, S. E. (Joint Fire Research Organization, Borehamwood, England) "Fires in Television Sets," *Joint Fire Research Organization Fire Research Note 804* (March 1970)

Section: L
Subjects: Casualties; Fire cause; Fire statistics; Television

Author's Summary

A recent fire in a hotel which occurred outside normal viewing hours but was attributed to a television set has prompted a study of the statistics of television fires. Fires in television sets more than doubled in frequency in the period 1960–1968. There were an estimated 1244 incidents in 1968 (based on a one-in-four sample of fire reports); only 56 of these occurred between 01.00 and 10.59.

Of those outside normal viewing hours, at least two-thirds occurred in sets that were said to have been left plugged in.

In the one-in-four sample of reports ten rescues and nine non-fatal casualties were noted.

Chandler, S. E. (Joint Fire Research Organization, Borehamwood, England) "Preliminary Analysis of Fire Reports from Fire Brigades in the United Kingdom, 1969)" *Joint Fire Research Organization Fire Research Note 815* (April 1970)

Section: L
Subject: Fire statistics

Chandler, S. E. (Joint Fire Research Organization, Borehamwood, England) "Fire Deaths in the First Quarter of 1970," *Joint Fire Research Organization Fire Research Note 825* (May 1970)

Sections: L, K
Subjects: Deaths; Fatalities; Fire deaths; Fire statistics

Author's Summary

A preliminary survey shows that 242 persons died in fires in the first quarter of 1970. Two hundred nine of these were in England and Wales, 30 in Scotland and three in Northern Ireland. This figure is slightly higher than the preliminary estimate for the first quarter of 1969.

The most serious incident was at a hospital in which five elderly men died. There were eleven deaths attributed to electric blankets in England and Wales, compared with three in the first quarters of each of the two previous years.

Chandler, S. E. (Joint Fire Research Organization, Borehamwood, England) "Fire Deaths in the Second Quarter of 1970," *Joint Fire Research Organization Fire Research Note 840* (August 1970)

Section: L
Subjects: Deaths; Fatalities; Fire deaths; Fire statistics

Author's Summary

A preliminary survey shows that at least 98 persons died in fires in England and Wales in the second quarter in 1970. The corresponding figures for Scotland and Northern Ireland were 34 and two, respectively. The figure for England and Wales shows a decrease of about 25 percent compared with the corresponding quarter in 1969. However, the Scottish figure has doubled.

The worst fire in the quarter occurred when oil on the surface of the Manchester ship canal became ignited, involved craft on the canal and resulted in five deaths.

Fry, J. F. (Joint Fire Research Organization, Borehamwood, England) "Town Gas Explosions in Dwellings," *Joint Fire Research Organization Fire Research Note 813* (March 1970)

Section: L
Subjects: Explosion; Dwellings; Gas, town; Statistics

Author's Summary

An examination has been made of fire brigade reports of incidents involving explosions of town gas in dwellings during the 12 years 1957–68. The average annual frequency was about 84 but appears to be increasing. The average rate of incidence is about 5.0 per 10^8 therms of gas sold. About 48 percent of incidents cause some structural damage and in 38 percent of these it is considered "severe."

Ramachandran, G. (Joint Fire Research Organization, Borehamwood, England) "An Enquiry into the Frequency of Sprinklered Premises," *Joint Fire Research Organization Fire Research Note 828*

Section: L
Subjects: Sprinkler; Building; Economics

Author's Summary

In order to assess the economic value of sprinklers it is first necessary to know the frequency of sprinklered premises in different types of occupancy. In this connection, a special survey was undertaken in 1965 with the help of the fire brigades. Results of the survey are discussed in this paper. Estimates of sprinklered establishments in different industries are also given.

Ramachandran, G., Kirsop, Patricia, and **Eveleigh, Christine** (Joint Fire Research Organization, Borehamwood, England) "Large Fires during 1969," *Joint Fire Research Organization Fire Research Note 829* (July 1970)

Section: L
Subjects: Fire, large; Fire loss; Fire statistics

Authors' Summary

This note contains an analysis of large fires during 1969. These are fires which cost £10,000 or more in direct damage. There were 1118 such fires during 1969 resulting in a total loss of £78.2 million. Of these, 60 were in outdoor hazards some of which spread to buildings.

Salzberg, F. (IIT Research Institute, Chicago, Illinois) "Fire Department Operations Analysis," *Report under Contract DAHC20-70-C-0208 for the Office of Civil Defense* (June 1970)

Sections: L, D
Subjects: Fire control; Fire department operations; Fire extinguishment; Fire fighting, equipment; Fire fighting, manpower; Fire fighting, time; Fire fighting, water usage

Author's Summary

Objective and Scope

In a previous study,* fire department operations within the Chicago Metropolitan Area were examined. Necessary data were obtained from reports prepared by fire chiefs acting as consultants to the project.

The objective of this study is to obtain data from a wider geographical area in order to refine and modify correlations previously developed. The scope of work

* Labes, W. G., "Fire Department Operations Analysis," IIT Research Institute Report for Office of Civil Defense, Contract DAHC20-70-C-0208, OCD Work Unit 2522F, January 1968.

consists of expanding the previous study to include the analysis and correlations of fire department operations in approximately 40 additional fires from four different regions in the United States which differ from the Chicago area.

Approach

The operational analysis was made from data received in reports from fire chiefs of four different cities. The cities are Los Angeles, Calif., Buena Park, Calif., New York, N.Y. and White Plains, N.Y.

In each report prepared, an attempt was made to provide a time history (as complete as possible) from the estimated ignition time to the final extinguishment and overhaul, including the time of arrival of each piece of fire department apparatus and the actual time required to bring the fire under control. All reports were prepared in a uniform manner on forms supplied to the fire chiefs by IITRI. Each report included plan view sketches indicating the location of the fire origin (where possible), the extent of the fire area, the location and description of hose lines and fire suppression apparatuses, and a narrative description of the fire.

For the analysis and correlation, the data have been grouped into two classes—residential and nonresidential. Except for those from Los Angeles, most of the fire reports were of residential fires. The data are compared to corresponding data from the Chicago area fires.

Significant Findings

1. Operations of fire departments within the four cities considered show similar trends to those determined for the Chicago Metropolitan Area.
2. The diverse types of fires and the small sample size (ten fires from each city) do not permit definitive conclusions regarding the observed differences in fire department operations in various cities.
3. Correlations developed using data from the Chicago Metropolitan Area provide interim information for other cities.
4. Brigade activities should be limited to knockdown of fires, leaving the final extinguishment to self-help teams.

Simard, A. J. (Forest Fire Research Institute, Canadian Forestry Service, Ottawa, Ontario, Canada) "Reference Manual and Summary of Test Fire, Fuel Moisture and Weather Observations Made by Canadian Forest Fire Researchers between 1931 and 1961," *Forest Fire Research Institute Information Report FF-X-25* (August 1970)

Sections: L, J
Subjects: Canada; Forest fire; Fuel moisture; Statistics, Canadian, 1931–61; Test fire

Contents and Author's Introduction

Contents

Between 1931 and 1961 Canadian forest fire researchers gathered a vast quantity of data on weather, fuel moisture, and test fire behavior. The original purpose of the data was primarily for the development of forest fire danger tables. The data was gathered at 11 field stations across Canada. Each station had several sites which were considered representative of the major timber types in the area. Some stations were kept active for several years, while others operated for only one or two seasons.

During this period, more than a million observations of various types were recorded. Over the years, much of the information has been analyzed in conjunction with specific projects which centered primarily around fire danger rating. On the other hand, much of the information has never been rigorously scrutinized, due to the sheer enormity of the amount of data. In addition, there is a considerable amount of information available which is usable in present and anticipated fire research studies.

With the advent of machine processing, it became possible to handle large quantities of information with much greater ease. For this reason, a project was started in 1960 under the direction of D. G. Fraser to transfer the pertinent information from field notes to punched cards. This has recently been completed, and the result is approximately 200,000 cards of weather, fuel moisture, and fire behavior information.

Because of the complexity of the data, a 3-card format was used. There was a separate card for weather, fire behavior, and fuel moisture information. Each card was coded with reference information so that all observations made at the same place and time could be matched.

Today, with the third generation computers firmly established, even machine processing of data is relatively inefficient and slow. Physically handling 200,000 cards is somewhat difficult when the data are at some distances from the computer facility. For this reason, all of the data have been placed on magnetic tape. This was not in itself sufficient to allow for efficient computer processing, however. The fuel moisture, fire behavior, and weather records had to be merged. While this would have been a relatively simple process for small batches of data on unit record equipment, the problem turned out to be quite complex when the entire body of data was considered. The data format was rearranged to allow for more efficient processing and greater ease of reading. With removal of the limitations imposed by an 80-column card, and the ability to store vast quantities of information on a single reel of tape, it was not possible to repeat portions of records several times, so that each newly created merged record was complete by itself.

Because it is felt that the information is now in a form which is useful to many persons involved in fire research, this manual has been prepared. Its purpose is to describe the data, and their format. Inventories by stations are also presented to give the reader an idea of the amount of various types of information that are available. Since the original code manuals (Fraser and Joly, 1961, 1962, 1963, 1965) which described the card format are out of print, the information contained therein is also summarized.

Throughout this paper there are many direct quotations from the above-mentioned code manuals. To reference each individually would only serve to confuse the present manual. Therefore, it may be assumed that all descriptions of card formats and data codes for other than merged or revised records contained herein were taken from the code manuals prepared by Fraser and Joly. It should be noted, however, that there have been a significant number of additions made to the codes listed in the aforementioned manuals. Every attempt has been made to complete the list of codes in this publication. All persons with the original manuals should either discard them and retain this report, or correct the original manuals.

This manual is in five sections. The first section describes the reference data (site, date, etc.), which are generally the same for all tapes. Then the weather, fuel moisture and test fire behaviour data are each discussed separately. The last section presents the author's views concerning potential uses for the data and the future work which should be carried out to improve the continuity and quality of the files. There are also three appendices containing inventories of the data.

In all, ten major and several smaller programs were written for this project, totalling about 3,060 lines of instructions. Total computer time required for production runs was about $3\frac{1}{2}$ hours exclusive of spooling operations which required an additional $8\frac{1}{2}$ hours. To simply list all these programs without explanatory notes would require an additional 75 pages. Since these programs are very specialized, interest in them is expected to be very limited. Therefore, anyone requiring information on the individual programs for developing alternate formats and merge operations can obtain it from the Forest Fire Research Institute. The major program titles and a flow chart for the project is shown in appendix IV.

Takata, A. N. (IIT Research Institute, Chicago, Illinois) "Mathematical Modeling of Fire Defenses—Part II," *Final Technical Report under Contract DAHC20-70-C-0209 for the Office of Civil Defense* (March 1970)

Sections: L, M
Subjects: Brigades; Building fires; Fire defenses; Fire department; Fire spread; Self-help teams

Author's Abstract and Summary

ABSTRACT

This report covers the development of a computer code to predict the effects of civilian and professional fire fighting on building fires initiated within an urban area by a nuclear attack. Cities are represented by a few thousand tracts, each of which is described in terms of the composition and size of its built-up area and the lengths and widths of firebreaks between it and built-up areas in adjacent tracts. The fire-fighting forces consist of two-man teams called self-help teams that can handle small fires in furnishings, four-man teams called brigades that can handle fully developed room fires in their early stages, and finally fire-department units.

Provisions are included for allocating these forces according to the size, type and numbers of buildings in each tract. Travel speeds are varied according to distance from ground zero as well as according to the character of the built-up area. Provisions are also included for delays in exiting from shelters and for the movement of reinforcements to tracts seriously threatened by fire.

SUMMARY

This report is concerned with the second phase of a two-phase study to develop a computer code for evaluating the effectiveness of civilian and professional fire-fighting units in controlling and suppressing fires caused by a nuclear attack on an urban area.

The contract work scope is:

> "Continuation and expansion of the work of modifying the IIT Research Institute fire-initiation and fire-spread model to take account of the fire-suppression activities so as to produce a more accurate and firmly based resultant model. Additional examination of the resultant fire-initiation and fire-spread model with respect to the sensitivity of its output result to variations in assumed initial conditions."

The analyses for the prediction of the initial ignitions and subsequent spread of fire from building to building are based on previous studies.[1] The analyses for the prediction of the effects of fire fighting are based on modifications and extensions of previous studies of fire fighting in a single tract.[2]

To provide for flexibility and minimal storage requirements, the computer code was prepared in two parts. The first part utilizes the results of the Ignition Code[1] and descriptions of the sizes and compositions of the built-up areas throughout a city to predict the numbers and locations of the fires started by the fireball. The first part of the code also utilizes the probabilities of fire spread between buildings by flame radiation and by firebrands to compute information that is later needed for the prediction of fire spread within and between tracts. The second part of the code performs periodic evaluations of the fire situation in each of the city's tracts using the initial distribution of the building fires, the above fire-spread information, and the numbers, disposition and capabilities of the fire-fighting forces.

The effectiveness of fire fighting depends not only on the numbers, disposition, and capabilities of the units but also on factors such as the vulnerability of the buildings to fire, amounts of debris along travel routes, and response times of fire-fighting units. In order to account for these factors, the following provisions were included in the code:

- Variations of travel speed according to the composition of the built-up area and the distance from ground zero
- Variations in the average time required to search a building for fire according to the composition of the built-up area
- Variations in the time required to start fire-fighting operations

Provisions are also included for reinforcing the fire-fighting forces in given tracts with given numbers of fire-department units at specific times following a nuclear detonation.

References

1. Takata, A. N.: "Development and Application of a Complete Fire-Spread Model," Vol. 1 (Developmental Phase), Contract N00228-67-C-1498, OCD Work Unit 2538B, IITRI Project J6109, June 1968.
2. Takata, A. N.: "Mathematical Modeling of Fire Defenses," Contract N00228-67-C-2081, OCD Work Unit 2526A, IITRI Project J6118, March 1969.

Warheit, G. and **Quarantelli, E. L.** (Disaster Research Center, The Ohio State University, Columbus, Ohio) "An Analysis of the Los Angeles Fire Department Operations during Watts," *Report under Contract OCD-PS-64-46 for Office of Civil Defense* (December 1969)

Section: L
Subjects: Fire department operations; Los Angeles; Systems analysis; Watts

Authors' Summary

This monograph examines in a sociological framework the operations of the Los Angeles *Fire Department* during the civil disturbance in August 1965. Three major components of the department are examined and it is shown how the structure and functioning of the organization was altered during the disturbance. Attention is given to modifications in *decision making*, handling of *tasks*, and the *patterns of communication* within the organization. The authors indicate how the larger community context and organizational relationships of the department probably affected its overall response to the crisis.

M. Model Studies and Scaling Laws

Butler, C. P. (U.S. Naval Radiological Defense Laboratory, San Francisco, California) "Camp Parks Mass Fires," *Report under Contract DAHC20-70-C-0219 for the Office of Civil Defense* (August 1969)

Section: M
Subjects: Building burn; Camp Parks; Carbon monoxide; Mass fires; Modeling; Radiation

Author's Summary

This work summarized experimental work on the dynamic characteristics of burning buildings, as studied with small plywood models and one full-scale barracks section.

Parameters measured include total energy release rate, total thermal radiation, and carbon monoxide concentrations at scaled street levels, as well as carbon monoxide concentrations in a model basement.

The ratios of total thermal radiation to total energy release rate at maximum burning time are: for a skirted model, 25 percent; for an unskirted model, 30 percent; and for the full-scale barracks section, 8 percent.

The logistics for conducting large building burns is described.

N. Instrumentation and Fire Equipment

Wilde, D. G. "High-Expansion Foam for Fighting Industrial Fires," *The Engineer* 226, 719–721 (1968)

Section: N
Subjects: Foam, high expansion; High expansion foam; Industrial fires

Abstract by Safety in Mines Research Establishment, England
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A method of fire fighting involving high-expansion foam was developed first in Britain, for use against certain types of mine fires. Modern foam-making units are being used increasingly by fire brigades as part of their normal equipment. This paper describes briefly the action of the foam in extinguishing fires, compares applications of the technique in Britain, U.S.A., and Russia, and quotes practical and experimental examples. The advantages of high-expansion foam as a means of fighting fires are enumerated and the prospects of further developments in the field of automatically-operated extinguishing systems, using foam, are assessed.

Brenden, J. J. (Forest Products Laboratory, U.S. Forest Service, Madison, Wisconsin) "Determining the Utility of a New Optical Test Procedure for Measuring Smoke from Various Wood Products," *U.S.D.A. Forest Service Research Paper FPL 137* (June 1970)

Section: N
Subjects: Optical test; Smoke; Wood

Author's Summary

The amount of smoke developed from a range of wood and wood-base products under controlled fire exposure was measured optically within a closed chamber. The purpose of this investigation was to determine the utility of this method of measuring smoke and the appropriateness of the parameters used for potential smoke development. To insure a wide range of smoke development, samples of 12 wood species and 10 wood-base panel products were selected and tested. The values for products are useful primarily in evaluating this new test method and should not be used for code classification of smoke densities or values.

When exposed to a flame in the chamber, representatives of the various wood species produced little smoke. With nonflaming exposure, the species gave off more smoke, and the smoke level was strongly dependent on the level of irradiation. The wood species could be broadly separated according to smoke production, but an exact classification of smoke yield was not possible with the limited number of tests in this study. The least amount of smoke for the panel products was observed from a laminated paperboard. Other panel products gave off smoke in widely ranging quantities depending on the irradiation level and whether the combustion was flaming or nonflaming. In rigid insulation board (plank), a fire-retardant paint coating was very effective in reducing smoke production.

The chamber used has three advantages over other methods of smoke measurement. The first advantage is that the smoke-density parameter is dimensionless, which means that this chamber method can be applied to a variety of room situations, burning areas, and light-path lengths. The second advantage is that the exposure conditions are carefully controlled and uniform. The third advantage is that flaming and nonflaming combustion measurements can be made separately and independently, unlike flame-spread tests in which the specimen is exposed to varying degrees of radiant energy and a moving flame front.

Baldwin, R. (Joint Fire Research Organization, Borehamwood, England) "The Use of Water in the Extinction of Fires by Brigades," *Joint Fire Research Organization Fire Research Note 803* (March 1970)

Sections: N, I
Subjects: Brigades; Extinguishing; Fire; Size; Time; Water

Author's Summary

Some American data on the relationship between the rate of application of water and the fire area and between the time taken to control the fire and the fire area are reviewed. Comparison with published British data suggests that in spite of different techniques and conditions, at this level of comparison, the results are very similar. The rate of application of water is about four times as great as in experimental fires, suggesting that the chief problems of fire fighting are operational.

Tucker, D. M. and **Nash, P.** (Joint Fire Research Organization, Borehamwood, England) "The Construction and Use of an Apparatus for Determining the Drainage Characteristics of High Expansion Foam," *Joint Fire Research Organization Fire Research Note 819* (June 1970)

Section: N
Subjects: Foam, drainage; Foam, high-expansion

Authors' Summary

This note describes the construction and use of an apparatus for measuring the drainage characteristics of high expansion foam. It is intended as a possible method for use with a specification for high expansion foam liquids.

Results of drainage measurements on different liquids are given.

Kirkman, H. B. (Consulting Engineer) and **Campbell, L. E.** (The Reliable Automatic Sprinkler Company) "Velocity Pressure Effect on Sprinkler System Discharge," *Fire Technology* 6(1), 68–72 (1970)

Section: N
Subjects: Discharge tests; Pressure effect; Sprinklers; Velocity effect

Abstract by Editor of *Fire Technology*. Reprinted by permission

After conducting a series of sprinkler discharge tests, the authors concluded that the use of velocity pressure in sprinkler system calculations will give a false picture of the ability of the system.

Hird, D., Rodriguez, A. and **Smith, D.** (Angus Fire Armour) "Foam—Its Efficiency in Tank Fires," *Fire Technology* 6(1), 5–12 (1970)

Section: N
Subjects: Fires, tank; Foam; Tank fires

Abstract by Editor of *Fire Technology*. Reprinted by permission

The increasing use of floating roof tanks for the storage of flammable liquids has given rise to a tendency toward using foam monitors for fire protection instead of fixed applicators. The authors studied the effect of application methods on foam efficiency and compared the effectiveness of two protein-based foams, Light Water, and a fluoroprotein foam known as F.P. 70.

Salzberg, F. and **Campbell, J.** (IIT Research Institute, Chicago, Illinois) "Aircraft Ground Fire Suppression and Rescue Systems—Current Technology Review," *Report under Contract F33657-69-C-1183 for U.S. Air Force Aero Propulsion Laboratory* (October 1969)

Section: N
Subjects: Aircraft fires; Extinguishing agents; Liquid fuel fires; Rescue equipment; Rescue from aircraft fires; Suppression equipment; Suppression of aircraft fires

Authors' Summary

The study gives an overview of the state-of-the-art of aircraft ground fire suppression and rescue. Subjects considered include: hostile characteristics of liquid fuel fires, effectiveness of suppression agents, and fire suppression equipment. Current research related to aircraft ground fire suppression and rescue is identified and future studies recommended.

O. Miscellaneous

SMRE Bibliography, 3rd Edition, 1969. Compiled by M. Belton.*

Section: O
Subject: SMRE Bibliography

Abstract by Safety in Mines Research Establishment, England
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This is a bibliography of the published work of the Safety in Mines Research Establishment and of the Establishment's predecessors, and of publications by other workers for whom these bodies provided facilities, research contracts or grants. The bibliography covers the period from the foundation of organised research in 1908 to the end of 1968. References to over 1700 publications (excluding visual aids) are arranged alphabetically by authors' names. Separate lists of Safety in Mines Research Board papers and SMRE Research Reports are also included. The subject index has been computer-generated and is based upon research work carried out at the Postgraduate School of Librarianship and Information Science, University of Sheffield.

U.S. Department of Agriculture, Forest Service, Washington, D.C.

"10 Standard Fire-Fighting Orders," TT-8-(5100), paper, 193 pp., 1969 (includes final examination insert). Available from the U.S. Government Printing Office, Washington, D.C. $1.25

"Introduction to the Fundamentals of Fire Behavior," TT-9-(5100), paper, 39 pp., 1969. Available from the U.S. Government Printing Office, Washington, D.C. 45 cents (answer separate, 10 cents)

"Clouds and Associated Fire Weather for Training Fire Behavior Specialists," paper, 8 pp., January 1970. U.S. Department of Agriculture, Forest Service, Washington, D.C.

Section: O
Subjects: Clouds; Education; Fire behavior; Fire orders; Fire weather; Programmed texts; Training

Reviewed by B. W. Kuvshinoff

The Forest Service has sponsored a number of programmed learning texts for training fire fighters, and has recently added the above titles to its list. The three texts focus on wildland fires and related topics, and therefore are of primary interest

* 333 pages. Price £1.18.0d. Postage and packing extra.

to the Forest Service. However, they are of considerable interest to the fire service at large as a useful training technique.

Programmed Instruction: What It Is

Programmed instruction is a teaching technique consisting of a planned procedure that guides the student in small increments through a subject. Each step is presented in a logical sequence that builds on preceding steps and itself serves as a foundation for succeeding ones. A typical program begins with simple, basic ideas on a subject and continues by introducing new ideas based on the information already covered, or reviews previous material from a different viewpoint. Throughout, the student is involved with the subject matter by being required to interact with the program. He may be asked to fill in a blank, solve a problem, match words, check multiple answers, draw a diagram, or perform some other act that is intended to reinforce the ideas that have been presented. This interaction between the student and the subject, through the medium of the program, is the key to the effectiveness of programmed learning.

A course of programmed instruction can be presented in a variety of ways: through specially designed teaching machines, by flash cards, by slides and motion pictures, by computers, or by printed texts. Texts have the distinction of containing complete courses in an economical and convenient manner without requiring special equipment. Not being bound to equipment, texts can be carried about and used by the student whenever he has time and wherever he happens to be.

Studies have shown that programmed instruction, in principle, is effective at every educational level (from preschool through graduate school), and has been used successfully to teach almost every subject to students of virtually every background and capability.[1] Despite this success, programmed instruction, as Wilbur Schramm of Stanford University points out, does not make other teaching methods obsolete. It is merely another teaching device that merits a place beside live instructors, textbooks, lectures, visual aids, motion pictures, workbooks, and chalkboards.[2]

So it is in the fire service: programmed texts can serve either as independent training media where educational facilities are not available, or as courses integrated into formal training programs.[3]

Applications of Programmed Texts

Programmed texts have been tested and used for a number of years, and we have learned that they are particularly adapted to fill two important educational needs. One is the classroom situation in which the students have mixed backgrounds and different learning rates. The virtue of programmed texts in this case is that they permit each student to set his own pace in completing the course. Faster students are not held back, and slower ones are not accelerated beyond their capabilities. The other situation is the one in which formal courses are not available, or the student for some reason cannot enter a formal educational program and therefore must resort to self-instruction.

Features of Programmed Texts

As mentioned, a programmed text presents elementary units of information to a student, and then requires him to exercise his new knowledge in some positive way. The single idea, datum, or elementary principle to be learned is given in a unit called a frame, which consists of a statement, often accompanied by an illustration and usually a question. In some texts the answer is given in a column to one side of the page and below the frame to which it responds. In practice, the student covers the answers with a cardboard or paper "slider" until he has responded to the question, then he moves the slider and checks his answer. In so-called branching, or scrambled texts, different answers lead the student to different pages and frames. A correct answer sends the student to the next step in the program, a partially correct answer sends him to a remedial frame for review, while an incorrect answer returns him to the initial frame of the topic to start over.

Review of the Programmed Texts

The first text, "10 Standard Fire Fighting Orders," is a copiously illustrated text with two or three frames per right-hand page. Left-hand pages are either blank, or carry an illustration or map (all of which show fire areas in red) relevant to the frames on the facing page. Answers are printed one frame down in a shaded column at the outer margins of the right-hand pages. The shading is so bold and the overprinting so light, the answers cannot be read out of the corner of the eye. Thus, a "slider" is unnecessary with this text. Ample space is provided for writing answers inside the frames. The illustrations (some of which include humorous little stick figures) clearly picture the situations being described.

Subject coverage, though based on the 10 standard fire-fighting orders of 1965 for wildland fires, extends to map-reading skills, fire behavior under various meteorological and forest conditions, and principles of fire-fighting tactics. Overall, this is a meaty text for novice fire fighters, and requires a student's concentrated attention to get everything out of it that it offers. The material is not difficult, provided the student memorizes the 10 orders that are listed inside the front cover.

The final examination consists of 13 questions, which require brief descriptions of fire conditions depicted on accompanying maps and the writing out of the standard fire-fighting orders.

The second text, "Introduction to the Fundamentals of Fire Behavior," covers, in an elementary fashion, seven fundamental concepts in fire behavior: (1) the fire triangle, (2) ignition temperature, (3) sources of heat, (4) heat transfer, (5) weather factors, (6) forest fuel factors, and (7) topography. This text has five frames per page: the first series at the tops of succeeding pages; the next, second from the top; and so forth. Thus, a student leafs through the booklet five times to complete the course, which according to the "Introduction" requires from $1\frac{1}{2}$ to 2 hours. The answer to the question in frame 1 appears to the left of frame 2 on the following page. Thus, the answer remains hidden from the student until he turns the page.

As titled, this is an introductory course, briefly covering the elementary concepts in fire behavior. By using the 6-page answer separate, or plain paper for that matter, the text itself is unmarked, and therefore it can be used by another student. For the economy-minded, this is an important consideration.

The third text, "Clouds and Associated Fire Weather for Training Fire Behavior Specialists," is a flip-type, pad-shaped text, 8 by 5¼ inches. This is a scrambled, or branching text in which the student is sent from page to page in random order, depending on the answers he gives to the questions asked. The student thus cannot anticipate where the correct answers are to be found until after he has responded.

The program begins on page 5 with a statement about clouds as indicators of five important fire-weather variables. The five variables are then listed. After studying this list, the student is instructed to turn to the next page. There he is asked to pick out the five variables from a list of ten items. He has three choices of answer printed at the bottom of the page. If he picks the five variables correctly, he is sent to page 4, which begins: "FINE—Clouds are only SYMPTOMS of atmospheric events . . ." This page then sends him to the next step in the program. If he picks one of the wrong answers, he is sent to page 2 or 3, both of which chide him on the wrong choice, comment on his error, and send him back to page 5. And so it continues through the booklet.

The wording is conversational. One page begins: "WHY NOT—Sorry: The statement is true." Then the student is given two choices: "1. I want to try again. (O.K.—TURN TO PAGE 42) 2. I would like to review clouds as indicators of wind. (Good idea—TURN TO PAGE 40)." Another page reads: "NO: Completely wrong—Better take a 5 minute break—then turn to PAGE 62 and re-read."

Having to go forward and backward through the booklet is slightly distracting, but the conversational nature of the program and the advice given on partially correct answers has the effect of drawing the student into a sort of contest with the program. At first introduction to the text, one has the disturbing feeling that the text has an uncanny omniscience about the student's errors; but of course, this is a feature built into the program. Specific ideas are reviewed for the student from time to time, often with additional information in different words or with a slightly different emphasis so as to correct misconceptions and put the student back on the right track.

This text contains many multiple-choice answers and word or phrase matching lists. This is a necessary technique in a scrambled text, because it attempts to discover a student's weaknesses in order to lead him to the proper review material. Designers of such questions almost invariably make at least three errors that help the student deduce the correct answer without having to know the subject matter. One or more of the answers or matches are patently (1) ridiculous, (2) contradictory, and/or (3) obvious. A student, quite naturally, eliminates the ridiculous and contradictory, answers the obvious, and then with just the faintest notion about the remainder, can sail through with a perfect score.

Even realizing that he scored correctly through trickery rather than mastery of the subject, few students can resist the beck of the path ahead. Most students will proceed with the program rather than backtrack to review their weaknesses.

Whether or not this is as bad as it appears may be debated. On the one hand the student has done some thinking and has exercized his deductive reasoning; on the other hand, however, a student can score extremely well in an examination of this kind merely with a superficial knowledge of half or less of the course material. Indeed, good scores may mislead him into thinking he knows more than he actually does.

Let us assume we have not studied the text at all, nor have we ever heard of cumulus, stratus, or cumulonimbus. Flipping through the book, suppose we stop at page 45, where we read:

Match the following:

A. Cumulus	X. Steady wind
B. Stratus or fog	Y. Very erratic and very gusty wind
C. Cumulonimbus	Z. Variable and gusty wind

1. A–X, B–Z, C–Y (PAGE 47)
2. A–Z, B–Y, B–X (PAGE 48)
3. A–Z, B–X, C–Y (PAGE 49)

Now, anyone old enough to take this course will have been in one kind of fog or another in his lifetime, or he would have seen a late-show rerun of Laird Cregar in "Jack the Ripper," at least half of which was shot in a dense London fog. He will remember that fog, if anything, tends to hang, or drift. Therefore, of the choices offered, B–X makes the most sensible match. B–X appears only in answers 2 and 3, so answer 1 is immediately eliminated. In 2 there is a contradiction, for if B–X is true, intuitively B–Y must be false. (Another reason why answer 2 is unlikely is that nowhere in the book is there anything but a one-to-one correspondence in such matching lists. Therefore, the appearance of two B's in the same answer immediately eliminates it from consideration.) Answer 3, therefore, is the only one that holds, and it is indeed the correct one. The reviewer was able to answer this question in precisely the manner described.

Similar reasoning can be applied to many of the other multiple choice lists in this text.

Surely a conscientious student would not subvert the course into a guessing game: but the challenge is so enticing, it is difficult to resist. The lure of the path of least effort is so inviting, one tends to skip ahead even though he realizes that he "beat the program" by a ploy, and should go back and restudy the subject material.

This criticism is not intended to condemn this particular text, which contains good material that is well presented. This discussion is meant merely to point out some of the frailties that often plague multiple-choice type questions

In general, the subject matter of clouds as fire weather indicators is covered rather completely, and in considerable depth. A conscientious student will find this text both absorbing and useful.

Conclusions

The programmed texts described above were found to be excellent training aids. The subject matter is presented in logical fashion and with good continuity, even in the case of the scrambled book. Each one has the potential of teaching its subject comprehensively to a student in a relatively short time. However, there is a strong impression that none of these texts either pretends to or can stand alone. Any student who wishes to acquire expertise in any of the subjects covered must also study traditional text books, monographs, and other types of literature. Despite the step-by-step buildup of the program and integration of each frame into the whole, this reviewer came away with the feeling that the material presented was characterized by a flatness: the subject matter lacked dimensionality. Not all facts or principles have equal importance, and all facts and principles are subordinate or superordinate to other facts and principles. A textbook, through a narrative continuum and topical structuring reveals the third dimension of a subject much more clearly than a programmed text is capable of doing. Perhaps this is an inherent characteristic of programmed texts and the one that relegates them to the category of adjunct to, rather than substitute for, other teaching and learning methods.

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1. U.S. Department of Health, Education and Welfare: "The Research on Programmed Instruction—An Annotated Bibliography." (1964).
2. SCHRAMM: "Programmed Instruction Today and Tomorrow," *Fund for the Advancement of Education* (1962).
3. National Fire Protection Association: "How to Build Fireman's Training Centers," 2nd ed., 80 pp. (1963) (Includes brief information on training programs in various states and Canada.)

TRANSLATION

Bunev, V. A., Melamed, B. M., Tud'panov, R. S., and **Khachaturian, V. M.** (Novosibirsk) "Limiting Characteristics of Self-Ignition in Methanol and Formaldehyde Mixtures," *Physics of Combustion and Explosion* **5**(1), 139–144 (1969). In Russian

Subjects: Formaldehyde; Methanol; Self-ignition; Thermal explosion

Translated by L. Holtschlag*

The kinetics of oxidation of methanol and formaldehyde have been insufficiently studied up to the present time. The literature data on the oxidation kinetics of methanol and formaldehyde differ strongly from each other, which is evident from the Table 1. The oxidation kinetics of methanol were studied in Ref. 1 at T = 420° to 460°C, at an initial pressure of 300–600 mm Hg, in a "clean" glass vessel (d=38 mm). The effective activation energy E_{eff}, calculated from the temperature dependence of the maximum heating ΔT_{max} in the center of the vessel, is 89.5 kcal/mole. The overall order of the reaction, n, in the expression for the maximum reaction rate $W_{max}=kp$ is 2.4, and in the expression for the maximum heating $\Delta T_{max}=kp^n$ it is n=2.8–3.3 for temperatures of 460° to 430°C, rep. If under the initial conditions the walls of the vessel are coated with platinum,[2] we have,

* Applied Physics Laboratory, The Johns Hopkins University. Translation 2429. By permission.

TABLE 1
Oxidation Kinetics of Methanol and Formaldehyde

Experimental Conditions	E_{eff} (kcal/mole)		T°C	Source
	Methanol			
Clean vessel	89.5	3.3–2.7	420–460	(1)
Walls covered with platinum	27.5	4.7	420–460	(2)
Walls treated with H_3BO_3 solution	38	—	390–460	(4)
Clean vessel	53–61	—	490–460	(4)
KCl solution	43	—	490–460	(4)
NaOH solution	44	1.3(CH_3OH)		
Clean Pyrex vessel	12	—	430–470	(4)
Used vessel	53	—	430–470	(4)
New vessel	61	—	430–470	(3)
	Formaldehyde			
Clean glass vessel	26		337–550	(5)
Walls treated with $K_2B_4O_7$ solution	50	—	337–550	(5)
Clean vessel	27.4	—	317–377	(6)
——	21.0	—	325–370	(7)
——	20.6	—	287–337	(8)
——	17.6	—	277–337	(9)
——	25	—	300–388	(10)
——	29.4	—	376–462	(11)

$E_{eff}=27.4$ kcal/mole. The order of the reaction with respect to the total pressure increases: $n=4.7$ instead of 3.3 in the "clean" vessel. The value of the effective activation energy also depends on the method of determining it. For example, the effective activation energy found from the temperature dependence of the maximum concentration of formaldehyde, is 12 kcal/mole, and from the dependence of the maximum velocity on T°K it is $E_{eff}=53$ kcal/mole.[3]

Analogous data were obtained for oxidation of the formaldehyde. In a vessel treated with $K_2B_4O_7$, the effective activation energy, determined from the temperature dependence of the oxidation rate of formaldehyde, is 50 kcal/mole, and 26 kcal/mole in a "clean" vessel.[5] In experiments with a "clean" vessel there is an appreciable induction period (up to one minute and more), which disappears when the surface of the vessel is treated with $K_2B_4O_7$.

Thus, the oxidation kinetics of methanol and formaldehyde (E_{eff}, n) depend on the state of the reactor surface. The wall effect can be explained, in all probability, by the presence of inactive products of the reaction of HO_2 on the wall, since the HO_2 radical is governing in the oxidation of methanol and formaldehyde.[3,4,12] It should be noted that all the above-examined investigations were carried out in vessels whose characteristic dimensions did not exceed 50 mm ($V\sim6.5$ cm^3) at a pressure of 300–600 mm Hg. The wall effect will probably still be considerable if the volume is increased. As shown in Ref. 13, the surface state of the vessel ($V\sim2$ l) near the self-ignition limit of n-heptane ($T=440°$ to 650°C) plays an important role, owing to the reaction H_2O_2 wall inactive products.

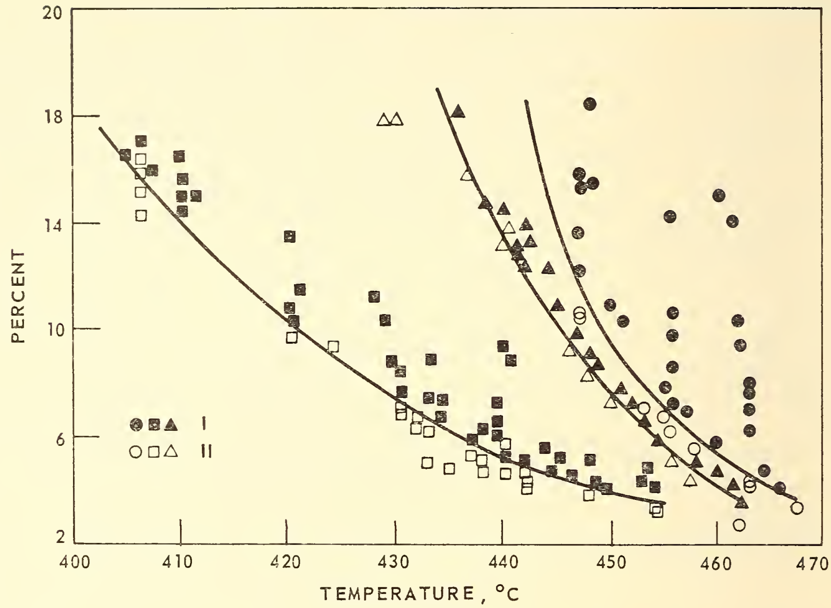

FIG. 1. Concentration limits for self-ignition of methanol and formaldehyde. 1—CH_2O—air mixtures; 2—23% addition of CH_2O to mixtures of CH_3OH and air, 3—CH_3OH—air mixtures; 1—self-ignition, 2—no self-ignition.

In the present paper the self-ignition of methanol and formaldehyde was studied in the apparatus described in Ref. 14. In a number of experiments, the surface of the reactor was treated with a 3 to 4% aqueous solution of KCl (chemically pure); the system was heated and evacuated over a period of 3 to 4 hours.

Shown in Fig. 1 are relations between the lower concentration limits for self-ignition of methanol and formaldehyde and the wall temperature of the reactor. The temperature range for formaldehyde mixtures was 405° to 455°C and 440° to 470°C for the methanol mixtures. The fuel concentration in the mixture with air varied from 3 to 18%. The self-ignition region for formaldehyde mixtures is wider than for methanol mixtures. The addition of 23% CH_2O [$(CH_2O)/(CH_3OH+(CH_2)$ 100%] to the methanol mixtures noticeably widens the self-ignition region of the methanol mixtures.

The values of E_{eff} were determined from the temperature dependence of the induction period (Fig. 2). The induction period turned out to be 10 to 35 sec for methanol and 3 to 11 sec for formaldehyde as a function of the temperature (13% per volume fuel concentration in the mixture). $E_{eff}=85$ kcal/mole ($T=445°$ to 470°C) for oxidation of methanol and E_{eff} 100 kcal/mole ($T=407°$ to 421°C) for formaldehyde. Using these values for E_{eff}, the concentration limits for self-ignition, assuming that the explosion is thermal in nature, the effective order of the reaction can be estimated from Frank-Kamenetskii's criterion for a spherical vessel. It was 1.32 for methanol mixtures, about 3 for formaldehyde mixtures, and 2.12 for the mixture 50% $CH_3OH+50\%$ CH_2O. It is well known that the oxidation of methanol is accelerated appreciably in the presence of formaldehyde.[15,16] This is connected with the fact that formaldehyde forms during the oxidation of methanol, resulting in degenerate branching according to the reaction.

$$CH_2O+O_2 \rightarrow HO_2+HCO$$

In the present paper, however, no appreciable reduction of the induction periods is observed when small additions of formaldehyde are introduced into the methanol mixtures. The nature of the dependence of the induction period on the quantity of formaldehyde additive (relative percentages) $T=456°C$) is shown in Fig. 3. As is evident from the figure, the addition of 5% CH_2O into a mixture containing 9.5% (per volume) of full reduces the induction period by a factor of 1.5, and by a factor of 1.3 in a mixture containing 13.5% full. The addition of 20% CH_2O reduces the induction period for the entire mixture by a factor of about 3.

When the reactor is treated with a KCl solution, the induction period in a region far from the limit remained invariable within the limits of the experimental accuracy. The lower limit of concentration for oxidation of methanol is shifted toward higher temperatures. For a mixture containing 13% per volume of methanol, the shift in critical temperature was 4.6 at an initial pressure of 1.2 atm and 9°C at an initial pressure of 0.6 atm, this shift was 9° at $\rho=1.2$ atm for a mixture containing 10% per volume of methanol.

In the case of slow methanol oxidation and of comparatively high pressures, the processes of chain continuation through the HO_2 radical begin to compete with the processes of radical destruction at the walls as a result of the deceleration of diffusion of HO_2 radicals to the walls. An increase in the probability of destruc-

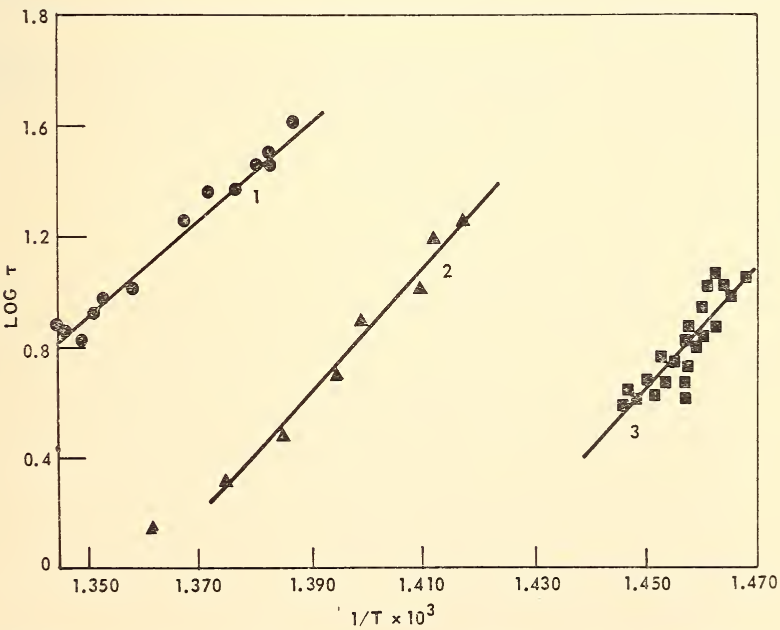

FIG. 2. Dependence of log τ on $1/T$. 1—methanol-air mixture; 2—formaldehyde air mixture; 3—50% CH_3OH+50% CH_2O air mixture.

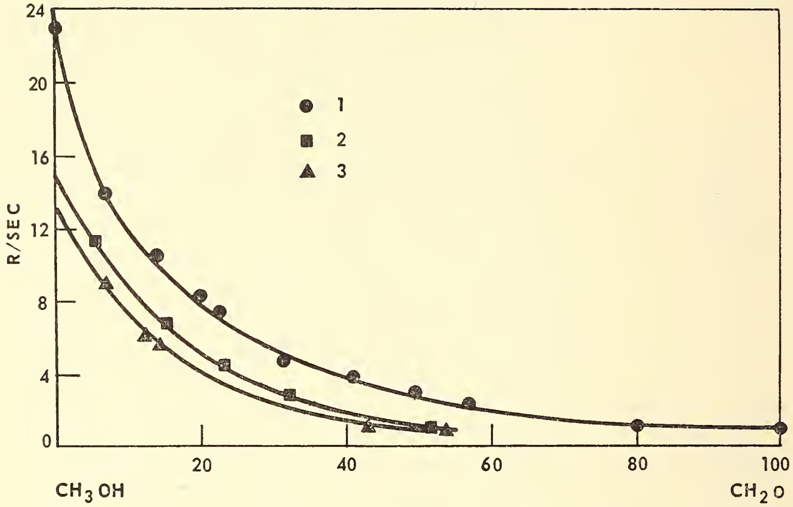

FIG. 3. Dependence of the induction period on the relative addition of CH_2 to methanol mixtures (T=456°C). Full content in %; 1—9.5; 2—13.5; 3—15.6.

tion of HO_2 (ξHO_2) radicals at the walls of a vessel cleansed with a KCl solution leads to faster chain rupture.[17] The wall effect should show up primarily in the limiting characteristics of the system (in the given case, in the ignition temperature). In regions far from the limit the surface effect is insignificant, which is confirmed by experiments on the determination of the induction periods in a reactor treated with KCl.

In our work we made an attempt to explain the results from the viewpoint of chemical kinetics. From an analysis of the literature data we chose the following scheme for the oxidation of formaldehyde:[11,13,16]

(1) $CH_2O+O_2 \rightarrow HCO+HO_2,$

(2) $HCO+O_2 \rightarrow CO \rightarrow HO_2,$

(3) $HO_2+HC_2O \rightarrow H_2O_2+HCO,$

(4) $HO_2^{\cdot} \xrightarrow[\text{wall}]{} \text{breaking}$

and of methanol:

(0) $CH_3OH+O_2 \rightarrow CH_2OH+HO_2,$

(1) $CH_3OH+HO_2 \rightarrow CH_2OH+H_2O_2$

(2) $CH_2OH+O_2 \rightarrow CH_2O+HO_2$

(3) $CH_2O+HO_2 \rightarrow H_2O_2+HCO$

(4) $HCO+O_2 \rightarrow CO+HO_2$

(5) $CH_2O+O_2 \rightarrow HCO+HO_2$

(6) $HO_2^{\cdot} \xrightarrow[\text{wall}]{} \text{products}$

Using the method of Semenov-Bodenstein and assuming that the concentration of original materials does not change, we can write the expression for the oxidation rate of formaldehyde and methanol, respectively, as

$$-d(CH_2O)/dt = k_1(CH_2O)(O_2) + (2k_1k_3/k_4)(CH_2O)^2(O_2),$$

$$-d[(CH_3OH)/dt] \sim k_0(CH_3OH)(O_2)$$

From the expression obtained for the oxidation rate of formaldehyde it is difficult to estimate the effective order of the reaction and the effective activation energy, since both terms are of the same order of magnitude. We can estimate the activation energy of the corresponding elementary events E_1, E_3, E_4. $E_1 = 32$ kcal/mole;[18] in conformity with Polyani's rule, E_3 can be estimated as $E_3 = 11.5 - 0.25 \times 12 = 7.5$ kcal/mole, where the thermal effect of reaction (3) is $q = 12$ kcal/mole; $E_4 = 6$ to 10 kcal/mole.[19] The total activation energy E_0 for the second term in the expression for the oxidation rate of formaldehyde is $E_0 = E_1 + E_3 - E_4 \sim 32$ kcal/mole. The first term in the expression for the rate contains only $E_1 = 32$ kcal/mole. On the basis of these data it is possible to conclude that the effective activation energy of the process of formaldehyde oxidation is about 32 kcal/mole for the given scheme.

The experimental value $E_{eff} \sim 100$ kcal/mole has been obtained. In the expression for the oxidation rate of methanol $E_{eff} \sim 45$ kcal/mole. On the basis of experimental data, $E_{eff} = 85$ kcal/mole, i.e., the oxidation schemes of both formaldehyde and methanol that can be written on the basis of literature data are not confirmed by our experimental data. This discrepancy is possibly connected with the fact that in the given schemes we did not take into account chain breaking in the volume, which can play a considerable role at sufficiently high pressures and large reactor volumes.

A quantitative estimate of the contribution of chain breaking in the volume cannot be made at present, apparently, on the basis of the existing experimental data. A more detailed study of the intermediate products during the oxidation of methanol and formaldehyde is required.

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MEETINGS

Conference Sponsored by Institute for Materials Research, National Bureau of Standards: *The Mechanisms of Pyrolysis, Oxidation, and Burning of Organic Materials.* National Bureau of Standards, Gaithersburg, Maryland. October 26–29, 1970

Chairman: Michael Szwarc
Genesis of Free Radical Chemistry—F. O. Rice
A Review of the Pyrolysis of Hydrocarbons—Alvin S. Gordon and R. H. Knipe
Pyrolysis of Hydrocarbons—Margaret Back
Chairman: Field H. Winslow
Factors Involved in Degradation of Polymers in Melts—William Bailey
Mechanisms of Polymer Pyrolysis—Leo A. Wall
Patterns and Problems in the Pyrolysis Behavior of Synthetic Addition Polymers—Gordon G. Cameron
Chairman: Field H. Winslow
On Certain Problems Connected with the Inhibited Oxidation Theory—Yu A. Shlyapnikov
Chairman: Simon H. Bauer
Oxidative Degradation of Polymers and Organic Compounds via Unimolecular Decomposition of Peroxy Radicals—Jean Marchal
Mechanisms of Oxidation of Polyolefins below 150°C—Frank R. Mayo
Chairman: J. R. McNesby
Mechanisms of Polymer-Gas Reactions (Air Pollutants): Influence of Polymer Morphology—H. H. G. Jellinek
Controlled Gaseous Oxidations of Organic Compounds—Charles Cullis
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Kinetics and Mechanisms in Flames and Flame Suppression—R. M. Fristrom
Chairman: Henry A. Hill
Carbon Formation in Premixed Hydrocarbon Flames—K. H. Homann
Chemical Kinetics in Combustion Reactions—E. A. Fletcher
Chairman: Robert Simha
Burning of Polymers—C. P. Fenimore and F. J. Martin
Chairman: Raymond Friedman
Pyrolysis and Burning of Cellulose—Raymond Alger
Surface Pyrolysis and Other Boundary Conditions for the Combustion of Polymers—Robert F. McAlevy, III

Eastern States Section of The Combustion Institute, *Kinetics of Combustion Reactions and the Mathematical Modeling of Flames.* Georgia Institute of Technology, Atlanta, Georgia, November 5 and 6, 1970.

Modeling

Chairman: A. Lloyd Thomson, McGill University

Theory of Multi-Diffusion Flames—T. M. Liu and H. H. Chiu, New York University

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An Investigation of Nonequilibrium Effects on Combustion in Supersonic Streams—R. M. Jensen, Wright-Patterson Air Force Base

Further Studies of Gas Turbine Combustor Modeling—D. C. Hammond, Jr., and A. M. Mello, Purdue University

Mathematical Modeling of a Swirl-Can Combustor—D. T. Pratt, C. T. Crowe, and B. R. Bowman, Washington State University

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Significance of Sensible Heats on Non-Isothermal Moving Boundary Analysis of Solid-Gas Reactions—R. C. Bailie, West Virginia University

Mathematical Modeling of Carbon Particle Combustion—J. B. Howard, Massachusetts Institute of Technology

The Simulation of Combustion Engineering Problems by Computer—L. Kurylko, Stevens Institute of Technology

Ignition and Oxides of Nitrogen Formation

Chairman: W. Bartok, Esso Research & Engineering

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Ignition of Unmixed Fuel and Oxidizer by a Hot Inert Gas—O. P. Sharma, S. P. Agarwal, and W. A. Sirignano, Princeton University

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Kinetics

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Flames, Ions, and an Electric Field: Shift in Species Concentration Profiles of a One-Dimensional Flame—K. Sridhar Iya, D. A. Crowl, P. M. Becker, and R. F. Heinsohn, Pennsylvania State University

High Temperature Thermal Dissociation of Carbonyl Fluoride—D. M. Weston and R. A. Matula, Drexel University

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The Combustion of Pure and Composite Propellants. The Expansion and Application of Laminar Flame Theory to Heterogeneous Solid Propellants—M. Hertzberg, Atlantic Research Corporation

Transient Phenomena of Reactive Fluid Flow in a Hybrid Rocket System—C. S. Chem, W. S. Y. Hung, J. K. Haviland, University of Virginia

Investigation of the Diffusion Flame between a Burning Polymer Surface and an Impinging Flow of Gaseous Oxidant—W. Blazowski and R. F. McAlevy III, Stevens Institute of Technology

Thermodynamic Considerations in the Mathematical Modeling of Unsteady Combustion of Solid Propellants and Implications in Ignition, Extinction and Oscillatory Combustion—R. L. Klaus, California Institute of Technology

Computed Surface Temperature of Nitrocellulose as a Function of Pressure—C. G. Irish, Jr., Olin Corporation

The Effect of Heat Recovery in Furnace Analysis—R. H. Essenhigh, Pennsylvania State University and Y-W. Tsai, P.P.G. Industr.

PERIODICALS

Fire Control Notes. Published quarterly by the U.S. Department of Agriculture, Forest Service*

Contents

Technical News Bulletin. Published monthly by the U.S. Department of Commerce, National Bureau of Standards.† Reprints from June 1969 issue

Thermophysical Properties Research Center Services

The Thermophysical Properties Research Center (TPRC), Purdue University, provides authoritative information and data on the thermophysical properties of all substances through comprehensive search and collection of the world literature. The Center, under the direction of Y. S. Touloukian, generates tables of data in

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its program of compilation and critical evaluation of existing data, theoretical studies, and experimental determinations. It also conducts research on thermophysical properties of materials. TPRC is financially supported by the Department of Defense, the Office of Standard Reference Data, and by commercial organizations; however, only the project on critical evaluation of data, a small part of its overall program, receives financial support from the Office of Standard Reference Data.

In its data compilation activities, TPRC is concerned with more than 25,000 different substances for the following thermophysical properties: thermal conductivity, accommodation coefficient, thermal contact conductance, thermal diffusivity, specific heat at constant pressure, viscosity, emittance, reflectance, absorptance, transmittance, solar absorptance to emittance ratio, Prandtl numbers, diffusion coefficient, thermal linear expansion coefficients, thermal volumetric expansion coefficients, and surface tensions.

The project on the critical evaluation of existing data and generation of recommended reference data currently covers the thermal conductivity of elements, oxides, liquids, and gases at all temperatures from absolute zero to the highest temperature measured, as well as covering the specific heats of liquids and gases.

Thus far, two critical compilations of data have been published, NSRDS-NBS-8, *Thermal Conductivity of Selected Materials*, Part 1, ($3, Clearinghouse No. PB189698), by R. W. Powell, C. Y. Ho, and P. E. Liley, and NSRDS-NBS-16, *Thermal Conductivity of Selected Materials*, Part 2, ($2, SD Catalog No. C13.48:16), by C. Y. Ho, R. W. Powell, and P. E. Liley. A comprehensive publication on thermal conductivity of the elements is now in preparation.

To implement its claim to comprehensive coverage of the world literature, TPRC operates two overseas divisions; one is in Kobe, Japan, and the other in Brussels, Belgium. These branches help to provide better service to the technical communities in Asia and Europe. The affiliate in Japan is completing its sixth year of continued operation under the direction of Tadashi Makita at Kobe University. During the past year, Professor Makita and his group have developed tables of recommended values for the specific heats of fluids, including refrigerants in the liquid and vapor phases. TPRC European branch is located at the Belgian Institute for High Pressure (IBHP) and is in its fourth year of operation. The IBHP is concerned with data generation involving the viscosity of gases and liquids. It is under the direction of Dr. Lewis Deffet with Dr. Pierre Hestermans serving as senior investigator.

TPRC offices at Purdue University receive many overseas visitors. Scholars from Belgium, Italy, Germany, and the U.S.S.R. are interacting with TPRC's program to contribute to TPRC's comprehensive coverage as well as to learn operations and procedures in documentation, critical data evaluation, and research in the area of TPRC's interests and competence.

The Thermophysical Properties Research Center invites inquiries from the U.S. and abroad. Communications should be addressed to Mr. William Shafer, Assistant Director-Technical, Thermophysical Properties Research Center, Purdue University, 2595 Yeager Road, West Lafayette, Ind. 47906.

COSATI Directory of Information Analysis Centers

The Committee on Scientific and Technical Information (COSATI) Panel on Information Analysis Centers, with the cooperation of the National Referral

Center, Library of Congress, has issued a revised *Directory of Federally Supported Information Analysis Centers* ($3, Clearinghouse No. PB189300).

As previously, the Directory is intentionally selective; inclusion was based on two specific qualifications: (1) The roster includes only those activities and programs operating within Federal Government agencies or being supported wholly or in part by Federal funds; (2) the roster includes only those activities that perform a majority of the functions within the scope of the Panel's definition of an information analysis center. The Panel's working definition of such a center was:

> An information analysis center is a formally structured organizational unit specifically (but not necessarily exclusively) established for the purpose of acquiring, selecting, storing, retrieving, evaluating, analyzing, and synthesizing a body of information and/or data in a clearly defined specialized field or pertaining to a specified mission with the intent of compiling, digesting, repackaging, or otherwise organizing in a form most authoritative, timely, and useful to a society of peers and management.

This publication should serve as a useful reference source for the identification of expertise in specialized fields. One hundred nineteen information analysis centers are listed in the Directory. Among information included for each entry are descriptions of mission, scope, services available, and user qualifications. For convenience, the Directory contains an index of subject areas covered, an index of names of center operators or directors, a list of organizations, and a list of locations. In addition, the centers are numbered serially to facilitate indexing.

COSATI Panel on Information Analysis Centers intends to keep the Directory current through issuance of either supplemental information or revisions at appropriate intervals. Users are requested to send omission or revision information to COSATI Panel on Information Analysis Centers, c/o the Office of Standard Reference Data, National Bureau of Standards, Washington, D.C. 20234.

Chemical Kinetics Information Center Lists of Publications

The NBS Chemical Kinetics Information Center collects and disseminates information on rates of thermal chemical reactions, cross sections of reactive collision processes, and quantum yields of photochemical processes. The center locates reports and other literature on these processes, indexes the processes, establishes and maintains a reference file and a subject index of the literature, and prepares bibliographies on specific topics. Among the reference lists it has recently prepared are the following NBS Lists of Publications:

1. Rates of decomposition of inorganic nitrates in solid phase and as fused salts, NBS LP 59, June 1969.
2. Rates of atom- and group-transfer reactions of iodine atoms in the gas phase, NBS LP 60, June 1969.
3. Rate of recombination of iodine atoms in the gas phase, NBS LP 61, June 1969.
4. Rates of reactions of peroxy-free radicals in the gas phase, NBS LP 62, July 1969.
5. Rates for radical-radical reactions in solution, the liquid phase and matrices, NBS LP 63, July 1969.

6. Gas phase rates for combination and disproportionation reactions of organic-free radicals, NBS LP 64, July 1969.
7. Rates of water exchange between metal complexes and the solvent, NBS LP 65, August 1969.
8. Rates of reactions of alkali metals with halogens in gas phase, NBS LP 66, April 1970.

These lists are available from the Chemical Kinetics Information Center, National Bureau of Standards, Washington, D.C. 20234.

Rate Data for Atomic Oxygen Reactions

A critical review by John T. Herron of the NBS Institute for Materials Research has been published in the *International Journal of Chemical Kinetics,* Vol. 1, No. 6, Nov. 1969. The review is entitled, An Evaluation of Rate Data for the Reactions of Atomic Oxygen (O^3P) With Methane and Ethane. This review presents in tabular and graphical form rate data on the reactions of atomic oxygen (O^3P) with methane and ethane. The reliability of these data is discussed and suggested values of the rate constants are given over specified temperature intervals. Specific values are given for reactions at 298 and 1000 K.

Rate constants have been reported for the reactions of atomic oxygen with a large number of organic compounds. The methane and ethane reactions are among the most carefully studied of these reactions. The purpose of this review was to tabulate the available rate data for methane and ethane reactions (excluding data published before 1950), and to arrive at suggested values for the rate constants at specified temperatures over specified temperature intervals.

This review was partially supported by the NBS Office of Standard Reference Data. A limited number of copies are available and requests for them should be addressed to Dr. J. T. Herron, Institute for Materials Research, National Bureau of Standards, Washington, D.C. 20234.

Thermodynamic Properties of Moist Air

NBS Building Science Series-21, Algorithms for Psychrometric Calculations (55 cents, SD Catalog No. C13.29/2:21), by T. Kusuda has recently been published. This paper provides step-by-step procedures for computer-oriented engineers in calculating accurate values of moist air properties. The method was described by J. A. Goff in 1949, but had not been previously adapted to computer techniques. The computerized method makes it possible to extend the well known ASHRAE tables (which are based on the Goff method) up to barometric pressures of 3 atmospheres and temperatures of 400 K. In addition, the method is believed valid for a mole fraction composition of dry air different from that used in the original calculation of the tables mentioned.

Very accurate values of moist air properties are required for many engineering problems. Notable examples are psychrometric calorimetry for measuring capacity of air-conditioning apparatus, moisture transfer analyses in cold storage warehouses, and analyses of simultaneous transfer of heat and moisture affecting the physiological responses of living organisms. Workers in these areas will find this publication helpful.

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ABSTRACTS AND REVIEWS

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Under the terms of its Congressional charter, the Academy is also called upon to act as an official—yet independent—adviser to the Federal Government in any matter of science and technology. This provision accounts for the close ties that have always existed between the Academy and the Government, although the Academy is not a governmental agency and its activities are not limited to those on behalf of the Government.

THE NATIONAL ACADEMY OF ENGINEERING was established on December 5, 1964. On that date the Council of the National Academy of Sciences, under the authority of its Act of Incorporation, adopted Articles of Organization bringing the National Academy of Engineering into being, independent and autonomous in its organization and the election of its members, and closely coordinated with the National Academy of Sciences in its advisory activities. The two Academies join in the furtherance of science and engineering and share the responsibility of advising the Federal Government, upon request, on any subject of science or technology.

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Supported by private and public contributions, grants, and contracts, and voluntary contributions of time and effort by several thousand of the nation's leading scientists and engineers, the Academies and their Research Council thus work to serve the national interest, to foster the sound development of science and engineering, and to promote their effective application for the benefit of society.

THE DIVISION OF ENGINEERING is one of the eight major Divisions into which the National Research Council is organized for the conduct of its work. Its membership includes representatives of the nation's leading technical societies as well as a number of members-at-large. Its Chairman is appointed by the Council of the Academy of Sciences upon nomination by the Council of the Academy of Engineering.

THE COMMITTEE ON FIRE RESEARCH functions within the Division of Engineering to stimulate and advise on research directed toward the development of new knowledge and new techniques that may aid in preventing or controlling wartime and peacetime fires. The Committee was established in December of 1955 at the request of the Federal Civil Defense Administration. It is supported by the Office of Civil Defense of the Department of the Army, the U.S. Department of Agriculture through the Forest Service, the National Science Foundation, and the National Bureau of Standards.